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Rapidly Deployable Systems (RDS) Underwater Acoustic Telemetry Trials Report

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ABSTRACT

Maritime surveillance of Australia's littoral waters and approaches is important to the defence and well being of its resources. Rapidly Deployable Systems (RDS) that can be safely delivered and deployed, and then interrogated and controlled from near and/or far, may provide an important force multiplier for the ADF. However, the efficiency of these systems will, amongst other things, depend on the performance of the external data telemetry link. This is particularly true of an underwater acoustic communication or telemetry link that may be used by a patrol to interrogate and extract contact data from a surveillance barrier.

This paper describes work done by the Maritime Operations Division Salisbury, to design, develop, and trial a simple, low cost, high data rate underwater acoustic telemetry system in a shallow water littoral environment.

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Executive Summary

Under the Rapidly Deployable Systems (RDS) task sponsored by DGMD, DSTO is investigating offboard ocean deployed sensors that can be rapidly deployed and monitored from near and/or far. Underwater Acoustic Communications (ACOMMS) or Telemetry Systems that use the water as the transmission medium could allow a submarine or other platform to approach, interrogate, and download data from an undersea rapidly deployable sensor system. By eliminating the need to use interconnecting cable links, these systems could provide future RDS with complete stealth connectivity and greater operational flexibility. The study of high data rate underwater ACOMMS systems by the Maritime Operations Division (MOD) Salisbury, has principally been focused on developing simple systems to test this concept.

This report describes the recent research conducted by the MOD Salisbury to investigate the problems/feasibility of using high data rate ACOMMS for short-range telemetry in shallow littoral waters. A relatively simple, low-cost experimental digital ACOMMS system, that used digital modulation techniques and differential signalling with no adaptive equalisation, beamforming or doppler correction, was designed, developed, and tested in the shallow littoral waters of the Gulf St. Vincent in South Australia.

Test results showed that by using a relatively simple, low-cost, digital ACOMMS system, a relatively error free high data rate transmission (in our case 16 kbaud or 32 kbps) could only be obtained over short ranges (up to 100 m in a 40 m deep offshore channel). However, as MOD and others have found, these results can only be obtained with the simplest of underwater channels ie. stationary type with fixed transmit and receive platforms. Should the fundamental properties of the channel change, or relative motion occur between the transmitter and receiver, then these changes can severely limit the performance of the ACOMMS system. To obtain robust ACOMMS performance the investigation and/or use of more sophisticated modulation, phase tracking, and space-time processing techniques is recommended. Although these techniques require more complex modulation/demodulation and transmitter/receiver structure they should provide improved and robust ACOMMS performance.

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Contents

1. Introduction

Under the Rapidly Deployable Systems (RDS) task sponsored by DGMD, DSTO is investigating offboard ocean deployed sensors that can be rapidly deployed and monitored from near and/or far. Underwater Acoustic Communications (ACOMMS) or telemetry systems that use the water as the transmission medium, could allow a submarine or other platform, to approach, interrogate, and download data from an undersea rapidly deployable sensor system. By eliminating the need to use interconnecting cable links, these systems could provide future RDS with complete stealth connectivity and greater operational flexibility. The study of high data rate underwater ACOMMS or telemetry systems by the Maritime Operations Division (MOD) Salisbury has principally been focused on developing simple systems to test this concept.

Results from the first RDS T1/98 Underwater Acoustic (UWA) telemetry trial (Appendix A) suggested that high data rate UWA communication, out to ranges of a few hundred meters in shallow water, may be possible using differential signalling and single path propagation techniques. The RDS T2/98 UWA telemetry trial was designed to test this theory and provide a better understanding of the effect the UWA communication channel has on the link performance. In addition, the acquisition and availability of real-time acoustic telemetry data would provide a valuable off-line data base for any future research into high data rate UWA telemetry systems.

The RDS T2/98 UWA telemetry trial and post trial analysis confirmed that the fundamental properties of the channel could severely limit digital ACOMMS. Signal degradations caused by multi-path propagation and the high temporal, spatial, and frequency variability of the channel, are the major problem. Results show that to achieve high data rate ACOMMS on all except the simplest of channels would require more than single path propagation techniques. As others have found, to achieve high data rates on band-limited UWA channels requires the use of band-width efficient modulation techniques, joint adaptive beamforming and equalisation, phase tracking, and the use of a high symbol rate to render time varying parameters almost stationary from symbol to symbol.

2. Experimental Telemetry System Concept

The aim was to develop a relatively simple, low cost, digital UWA telemetry system, that would enable research of high data rate ACOMMS to be conducted without using complex modulation/demodulation and transmit/receiver structure ie. phase coherent signal detection, array processing, and equalisation. The system was designed to operate at short ranges in shallow water. A brief experimental system specification is shown in Table 1.

Table 1 Experimental UWA Telemetry System Specification

System/sub-system	Parameter	Specification
System	Range	Up to 500m
	Depths	5m to 100m
Modulation	Format	4 - DPSK
	Carrier Frequency (fc)	65,564 Hz
	Data Rate	fc/2 bps
Transmitter	Source Level	≥175dB re μPa rms
	frequency range	(50 – 80) kHz
	Beam Pattern	Toroidal
	Tx Mode	Continuous & Pulsed
	Tx Pattern	2^17-1 PRBS & All '1' binary
Receiver	Type	Directional (DI~18dB) and/or Omni-directional
	Bits/sample	1

A schematic of the experimental system is shown in Figure 1. It comprises an autonomous underwater transmitter, transmit and receive transducers, acoustic channel, and an on-board receiver. The transmitter comprises a pre-programmed binary data source, 4 -DPSK modulator, power amplifier, matching transformer, and own power pack. The transmit transducer is an ITC-2039, Free Flooded Ring, useable frequency range 50-80 kHz, resonant frequency 65kHz, and Source Level 175 dB re 1μPa rms. The receiving transducer is a purpose built ITC-3441 hydrophone, with a Directivity Index of 18dB. For comparison, a frequency compatible LC10 omni-directional hydrophone with 60dB built-in preamplifier was also used. The on-board receiver included an input filter with preamplifier, 4-DPSK 1bit/sample digital demodulator, detector, and appropriate monitoring and recording equipment.

3. Trial Report & Records

3.1 Sea Trial

Sea trials of the experimental UWA telemetry system have been successfully completed in the Gulf of St. Vincent in accordance with the procedure given in Annex C of the RDS T2/98 Trials Instruction [1]. As planned, the scheduled Shallow Water Acoustic Telemetry (SWAT) tests were conducted at Site A, using the MRV Ngerin, in 40m of water and ideal weather conditions. However, the proposed Deep Water Acoustic Telemetry (DWAT) test scheduled for Site C, in 100m of water, 10nm south of South Neptune Island, was not conducted because the MRV Ngerin was not able to anchor in

water deeper than 60m. In lieu of this, an additional burst (pulsed) type underwater acoustic transmit mode was tried and tested at Site A, to study and investigate the effect of using pulsed or burst mode transmission to overcome the effects of multi-path propagation.

The experimental trials set up is shown in Figure 2. It provided a flexible arrangement in which the range and depth of the transmitting transducer could be varied without leaving the ship. At the same time, the overboard support and steering mechanism could be used to manually steer the directional hydrophone (receiving transducer), towards the buoy and suspended underwater transmitter.

3.2 Records

A HP Signal Analyser was used to monitor and check the power spectrum of the received signal. Selected samples of the output signal of each respective hydrophone preamplifier were then recorded on a 14 channel TEAC XR-510 cassette data recorder. The received signal Bit Error Rate (BER) was only recorded for the continuous all '1' binary sequence because, during the trial the 4 - DPSK demodulator could not synchronise and correctly demodulate either the received Pseudo Random Binary Sequence (PRBS) or the all '1' binary pulse sequences.

3.2.1 Tape

In accordance with the procedure outlined in Annex C of the RDS T2/98 Trials Instruction [1], tape records of the received time series data for each SWAT run were made at each of the proposed ranges. With the cancellation of the Deep Water Acoustic Telemetry (DWAT) test at Site C, all tests were subsequently conducted at Site A in 40m of water, including the additional all '1' binary pulse sequence. The trial schedule and actual recording times are shown in Table 2, and the corresponding underwater acoustic telemetry tape records are listed in Table 3.

All test runs were conducted using a bit rate of 32,782bps ie. half the carrier frequency, with either a continuous (2^{17}-1) bit PRBS, a continuous all '1' binary sequence, or a pulsed (1msec burst, 1s pulse repetition rate) all '1' binary sequence. Where possible, the BER of the received signal was recorded and used to establish the maximum measurement range. However, where this was not possible, the length of the available surface tether ultimately determined the maximum test range. To cater for the expected received signal bandwidth (40-90kHz), all tape records were made at 76cm/s. Each tape contains 24 minutes of received time series data comprising 6 x 4 minute tracks, with each track comprising 2 (part A & part B) x 2 minute records. All up, a total of 2 hours ie. 5 x 24 minutes, of received time series data was recorded.

3.2.2 CTD

CTD readings were taken on each day of the acoustic telemetry trial, and the corresponding Sound Speed Profiles (SSP) are shown in Figure 3. Except for day 2 of the trial ie.1Sept98, the SSP are all slightly downward refracting. Thus, for all post trial analyses, the SSP profile was assumed to be constant with a velocity of 1503m/s.

3.2.3 Wave files

Wave files of the recorded received signal time series data were generated by replaying each tape record at 1/8th of the original recording speed ie. 9.5cm/s, and using the PC based sound card to select a 10s time slot of each. In real time, each wave file contains 1.25s of real time data sampled at a rate of (22050x8) samples/s ie. 2 x maximum signal frequency, where the sample rate of the sound card is 22050 samples/s. These files are stored at I:\rds\T2_98\Tape#\Track_#.wav, and all acquisitions and analyses of the data stored in these files were performed using Matlab ©.

Table 2 RDS T2/98 UWA Telemetry Tape Records Schedule

Day	Date	Trail	Tape #	Run #	Tx Mode / Pattern	Recording Times (CST)
Monday	31Aug98	SWAT	1	1 & 5	CW / 2^17-1 bit PRBS	1925 to 2114
"	"	"	2	3 & 7	"	2141 to 2305
Tuesday	1Sept98	"	3	4 & 8	CW / All '1' Binary Sequence.	1408 to 1602
"	"	"	4	2 & 6	CW / 2^17-1 bit PRBS	1658 to 1749
Wednesday	2Sept98	DWAT	Cancelled because MRV Ngerin was unable to anchor in water deeper than 60m			
Thursday	3Sept98	SWAT	5	Additional run	Pulsed / All '1' Binary Sequence.	1006 to 1130

Table 3 *RDS T2/98 UWA Telemetry Tape Records*

Tape No.	Track No.	Tx Mode	Tx Pattern	Rx Type	Tx Depth (m)	Horiz. Tx/Rx Range (m)	Rx Gain Setting (dB)	Recorder I/P Range (V)	Tape count Start	Stop	BER
1 (1)	1A	CW	2^17-1 bit PRBS	Omni (2)	10	20	0	2	0	1118	(5)
"	1B	"	"	Directional (3)	"	20	0	2	1119	1740	"
"	2A	"	"	Directional	"	40	0	2	0	0904	"
"	2B	"	"	Omni	"	40	0	2	0905	1741	"
"	3A	"	"	Directional	"	90	+20	5	0	0904	"
"	3B	"	"	Omni	"	90	+20	5	0905	1741	"
"	4A	"	"	Omni	"	140	+20	2	0	0904	"
"	4B	"	"	Directional	"	140	+20	2	0905	1740	"
"	5A	"	"	Directional	"	190	+20	2	0	0859	"
"	5B	"	"	Omni	"	190	+20	2	0860	1741	"
"	6A	"	"	Omni	"	240	+20	2	0	1100	"
"	6B	"	"	Directional	"	240	+20	2	1101	1741	"
2 (1)	1A	CW	2^17-1 bit PRBS	Omni	30	20	+20	5	0	0900	(5)
"	1B	"	"	"	"	40	+20	5	0901	1741	"
"	2A (4)	"	"	Directional	"	90	+40	10	0	0900	"
"	2B	"	"	Omni	"	90	+20	5	0901	1747	"
"	3A	"	"	"	"	140	+20	2	0	0899	"
"	3B (4)	"	"	Directional	"	140	+40	10	0900	1741	"
"	4A (4)	"	"	"	"	190	+40	10	0	0894	"
"	4B	"	"	Omni	"	190	+20	2	0895	1748	"
"	5A	"	"	Directional	"	240	+20	2	0	0897	"
"	5B	"	"	Omni	"	240	+20	2	0898	1748	"
"	6A	"	"	Directional	"	190	+20	2	0	0900	"
"	6B	"	"	"	"	140	+20	2	0901	1748	"
3 (1)	1A	CW	All '1' Binary Sq	Omni	20	20	+20	10	0	0900	1.4E-3
"	1B	"	"	Directional	"	20	+20	2	0901	1741	1.3E-4
"	2A	"	"	"	"	50	+40	5	0	0897	2.0E-4
"	2B	"	"	Omni	"	50	+20	5	0898	1740	3.0E-2
"	3A	"	"	"	"	100	+20	5	0	0903	4.0E-2
"	3B	"	"	Directional	"	100	+20	2	0904	1740	1.5E-4
"	4A	"	"	"	"	150	+40	10	0	0897	1.0E-3
"	4B	"	"	Omni	"	150	+40	10	0898	1716	2.0E-2
"	5A	"	"	"	"	190	+20	2	0	0916	3.0E-2
"	5B	"	"	Directional	"	190	+40	10	0917	1727	2.5E-2
"	6A	"	"	"	"	300	+40	10	0	0902	6.0E-2
"	6B	"	"	Omni	"	300	+40	10	0903	1728	(5)

Tape No.	Track No.	Tx Mode	Tx Pattern	Rx Type	Tx Depth (m)	Horiz. Tx/Rx Range (m)	Rx Gain Setting (dB)	Recorder I/P Range (V)	Tape count Start	Tape count Stop	BER
4 (1)	1A	CW	2^17-1 bit PRBS	Omni	20	300	+40	10	0	0901	(5)
"	1B	"	"	Directional	"	300	+40	10	0902	1740	"
"	2A	"	"	"	"	200	+40	10	0	0898	"
"	2B	"	"	Omni	"	200	+20	2	0898	1748	"
"	3A	"	"	"	"	150	+20	2	0	0903	"
"	3B	"	"	Directional	"	150	+20	2	0904	1748	"
"	4A	"	"	"	"	100	+20	2	0	0901	"
"	4B	"	"	Omni	"	100	+20	5	0902	1740	"
"	5A	"	"	"	"	50	+20	10	0	0897	"
"	5B	"	"	Directional	"	50	+20	5	0898	1748	"
"	6A	"	"	"	"	20	+20	2	0	0900	"
"	6B	"	"	Omni	"	20	+20	10	0901	1748	"
5 (1)	1A	Pulsed (6)	All '1' Binary Sq	Directional	20	50	+20	5	0	0907	(5)
"	1B	"	"	Omni	"	50	+20	5	0908	1740	"
"	2A	"	"	"	"	100	+20	5	0	0973	"
"	2B	"	"	Directional	"	100	+20	5	0974	1743	"
"	3A	"	"	"	"	150	+20	2	0	0907	"
"	3B	"	"	Omni	"	150	+20	2	0908	1743	"
"	4A	"	"	"	"	200	+40	10	0	0906	"
"	4B	"	"	Directional	"	200	+40	10	0907	1744	"
"	5A	"	"	"	"	300	+40	5	0	0901	"
"	5B	"	"	Omni	"	300	+40	5	0902	1744	"
"	6A	"	"	"	"	20	0	0.5	0	0905	"
"	6B	"	"	Directional	"	20	+20	2	0906	1744	"

Notes:- 1. Water Depth = 40m , Receiver Depth = 5m
2. Omni-directional receiving hydrophone, type LC10 with 60dB built-in preamplifier.
3. Directional receiving hydrophone, type ITC -3441 with 40dB built-in preamplifier.
4. Invalid Record, by accident the ITC-3441 Directional receiving hydrophone was misaligned by 180° ie. directed away from the transmitting transducer.
5. BER>0.1, actual value not recorded.
6. 1msec burst, prr = 1sec

4. Results

4.1 UWA Channel

It is well known that the fundamental properties of the UWA communication channel can cause major problems for high-speed data communications. These problems include multi-path propagation, transmission loss, and the temporal or time varying nature of the channel. One of the trial aims was to obtain a better understanding of these problems by being able to predict and observe the effect each has on the acoustic signal as the depth and range of the transmitter was varied relative to a fixed receiver. The predictions and results follow.

4.1.1 Multi-path

Multi-path propagation causes dispersion or spreading of the signal in time and space. This in turn can cause frequency and space-selective-fading which respectively means that the received signal amplitude depends on frequency and the spatial location of the receiver. According to Stojanovic [2], the mechanism of multi-path formation depends on the channel geometry and the frequency of the transmitted signal. In a shallow water channel, the principal mechanism of multi-path formation is reflection of the signal at the surface and bottom boundaries, and any other waterborne objects. A ray diagram for the RDS T2/98 trial scenario is depicted in Figure 4(a) and the time-lag and relative power for the multi-path arrivals, as predicted by MODRAY [3] for a continuous frequency signal of 65kHz ie. the carrier frequency, is shown in Figure 4(b). These predictions suggest that the effects of the multi-path propagation may increase with the range and depth of the transmitter as the multi-paths converge towards the Direct Path (DP) signal, and the trial results did confirm this.

Typical results of the received signal power spectral density (PSD), measured at the hydrophone location for various ranges and transmitter depths of 10m and 30m respectively, are shown in Figures 5 and 6 respectively. It is clear from these plots that the channel multi-path has had an effect. In particular, each plot has the characteristic 32kHz wide, 4-DPSK modulated signal bandwidth with different levels of periodicity (frequency-selective-fading) and PSD, depending on the range and depth of the transmitter. Each plot was generated by averaging (>50 averages) the PSD obtained using a 4096 point FFT with Hanning window, 0% overlap, and typically 220k point sample.

4.1.2 Transmission Loss

The free-field acoustic Transmission Loss (TL) is comprised of two parts, a spreading loss and an absorption loss. The spreading loss is independent of frequency and is equal to $10\log10(r)^n$ where r is the range in metres, and n=2 for spherical spreading and 1 for cylindrical spreading. Absorption loss however, increases with range and roughly the square of the frequency. This limits the maximum operating frequency and bandwidth of the system. According to Catipovic [4], most UWA telemetry systems

operate within the lower one octave band of the attenuation limited frequency ie. the frequency at which the signal suffers a 10 dB absorption loss at the maximum desired range. In the case of the experimental RDS T2/98 telemetry system, the attenuation limited frequency was determined to be ~90kHz for a maximum operating range of 500m. The corresponding operating frequency range, or lower one octave band, was therefore 45kHz to 90kHz. With a specified frequency range of 50kHz to 80kHz, resonant frequency of 65kHz, and other appropriate transmitting characteristics, the ITC-2039 Free Flooded Ring (FFR) transducer was an obvious choice for the transmit transducer.

When only a rough approximation of TL is required, the ubiquitous spherical-spreading law plus absorption loss is adequate [5]. However, in a shallow water channel where specific propagation conditions exist, ray and or modal models such as MODRAY [3] and KRAKENC [6] provide a more explicit picture of what can be expected. The KRAKENC model predictions of TL, for the RDS T2/98 trial scenario, are shown in Figure 7 for a 65kHz frequency tone. The channel was assumed to be 40m deep and bounded by a flat sea surface and bottom comprising a mixture of sand, mud, and shells. The SSP was assumed to be constant with a velocity of 1503m/s. As the model predicts, the TL will be periodic and have significant spatial variability. Likewise, for a given channel with fixed transmit and receive geometry, a similar frequency variability can be expected.

The PSD plots shown in Figures 8 & 9 are a sample of the averaged, in water, received signal PSD recorded with the LC10 omni-directional hydrophone and the ITC-3441 directional hydrophone at various ranges. In both cases, the depth of the receiving hydrophone and transmit transducer was respectively 5m and 20m. If the PSD values measured at the carrier frequency ie. 65khz, are compared with those predicted assuming spherical-spreading and KRAKENC, there are some notable discrepancies. This is best summarised in Table 4, where the predicted in water received signal PSD levels at the hydrophone location, (assuming a SL of 175dB re 1μPa rms and attenuation of 0.02dB/m at 65khz for spherical-spreading) are compared with the values read from Figures 8 & 9.

Table 4 Received carrier signal, PSD levels

Range (m)	Predicted PSD (dB re 1μPa^2/Hz)		Measured PSD (dB re 1μPa^2/Hz)	
	Spherical spreading	KRAKENC model	LC-10 Omni-hydrophone	ITC-3441 Directional-hydrophone
50	124	124	120	126
150	112	112	120	116
200	109	117	115	96
300	103	107	97	95

However, these discrepancies can be explained by the fact that channel can cause considerable spatial variability, and a slight error in range and depth can change the TL and received signal PSD by as much as 30dB (refer Figure 7), especially at these higher signal frequencies and short wavelengths. Besides, for practical reasons, the ITC-3441 was mounted 0.5m above the LC10 on the pole of the overboard support and steering mechanism (see Figure 2). Similar results were observed for each of the other test runs.

4.1.3 Time varying

The dynamic or time varying nature of the channel, is caused by the random signal fluctuations or *micro multi-path* signals associated with each multi-path signal [2], and where applicable the relative motion of the transmitter and receiver [7]. For the shallow water channel with stationary transmitter and receiver, the major source of temporal variability in underwater acoustic transmissions is surface scattering by waves. This surface wave motion, frequency modulates the carrier frequency causing Doppler spreading which can manifest itself as fast or time-selective-fading. By assuming a fixed channel geometry and sinusoidal surface displacement, the Doppler spread caused by surface wave motion to the first major surface reflected multi-path (SS1 in Figure 4a), can be predicted for various surface wind speeds [2]. For example, the expected Doppler spreads for a 65kHz carrier frequency with transmit and receive transducers separated in range by 300m, and located at nominal depths of 20m and 5m respectively, are shown in Table 5 for various Sea States and wind speeds.

Table 5 Predicted Doppler Spread versus Sea State

Sea State		1	2	3	4
Wind Speed, w	knots	3	6	10	20
	m/sec	1.5	3	5	10
Wave frequency, f_w $=2/w$	Hz	1.3	0.67	0.4	0.2
rms Wave height, h_w $=5E\text{-}03w^{\wedge}2.5$	m	0.014	0.078	0.28	1.58
Doppler spread, B_w $=2f_w(1 + 4\pi f_c \cos\theta * h_w / c)$	Hz	4.3	6.1	11	29
Channel coherence time $= 1/B_w$	sec	0.23	0.16	0.09	0.03

As shown, the Doppler spread increases with increasing wind speed. Conversely, the estimated channel coherence time ie. the time that the channel impulse response is essentially invariant, decreases with increasing wind speed. During the course of the trial, it was hoped that the above effects would be observed. Unfortunately, the Sea State never exceeded 1 during the trial and the effect of surface wave motion was not observed.

A typical sampled version of the real-time received signal waveform and PSD versus time is shown in Figure 10. The effective sample rate was 176400 samples per second.

The red, green, and blue PSD plots, are the averaged received signal PSD of 3 consecutive 283 msec time slots, obtained using the ITC-3441 directional transducer and a 4096 point FFT with Hanning window, 75% overlap, and a 50k point sample. Likewise, the yellow plot is the averaged received signal PSD plot of the total sample, which represents about 1.3 seconds of real-time data. Although these are PSD plots of the received signal, any scalloping and significant variation over time, can be attributed to the channel. As can be seen, all plots show some periodicity (ie. frequency-selective-fading), due of course to the multi-path time spread. However, as expected, the PSD plots of the 3 consecutive 283msec and 1.3 second time slots show negligible variation, confirming the channel was essentially stationary.

4.2 DPSK Transmission

A 4–DPSK digital carrier modulation was selected to avoid the need for complex carrier recovery and to provide the required signal power-bandwidth requirements along with the expected phase tracking capability. This semi-coherent modulation scheme does not require knowledge of the absolute phase of the carrier at the receiver to work and only requires the channel characteristics to remain time invariant for 2 symbol periods. However, it still requires perfect knowledge of the bit duration and precise bit synchronisation to work.

For the experimental 4-DPSK system with 65564Hz carrier and information rate of 16391 symbol/s, the expected channel coherence times and fading rates (a slow fading channel has a large coherence time and visa versa) are listed in Table 5. These are much slower than the information rate. Because of this, the expected differential phase fluctuation due to the channel changing in a symbol period should be negligible. Differential signalling should therefore be sufficient to combat any expected channel induced signal fluctuations provided they are due to wave action alone and not the relative motion of the transmitter and receiver or other sources of Doppler spread. Likewise, given that the bandwidth efficiency of the 4-DPSK modulation scheme is 1bit/s/Hz, the bandwidth of the ITC-3441 transmit transducer should have been just adequate to achieve a data throughput of twice the symbol rate ie. 32782 bits/s. Power wise, differential PSK requires slightly more (~2.3dB) average signal power than coherent PSK for the same bit error rate (1 in 1E04). However, at ranges less than 1km, this was not considered to be a problem.

The results of the BER test made with the transmitter at mid-water depth and using the continuous all '1' binary sequence, are shown in Figure 11. As can be seen, the ITC-3441 directional hydrophone achieved a BER of better than or equal to 1E-03 out to 150m compared to 20m for the LC10 omni-directional hydrophone. In hindsight, this result was expected because the directional characteristics of the ITC-3441 directional hydrophone would have provided some space-selective-filtering which should have attenuated some of the multi-path signals and reduced the inter-symbol interference. No BER measurements were possible with either the continuous PRBS or burst mode transmissions because of the inherent receiver synchronisation problems.

4.3 Beamforming

Where equalisation is not deemed to be feasible because the underwater channel exhibits fading that is too rapid for an adaptive equaliser to follow, then the approach has been to use differential signalling and array processing to eliminate or suppress the multi-path [2]. To ensure complete absence of multi-path, highly directional transmit and receive beams are carefully positioned to obtain a single path of propagation. A similar approach was taken with the experimental UWA telemetry system, except for practical reasons, commercial off the shelf (COTS) transducers with fixed and moderately directional beam patterns were used. The transmitting transducer used was an ITC-2039 Free Flooded Ring (FRR). It has a toroidal beam pattern with 360 degree coverage which eliminates the need to manually steer it towards the receiving transducer (hydrophone). Similarly, the receiving transducer was a purpose built ITC-3441 hydrophone. It has a 10 degree vertical x 60 degree horizontal beamwidth at 65khz and was required to be manually steered towards the transmitting transducer.

Although the above arrangement would not guarantee a single path of propagation, the signalling rate obtained with the directional hydrophone was expected to be better than that obtained with an omni-directional hydrophone. This was because the directional hydrophone would not only improve the received SNR, but would also better attenuate the multi-path arrivals and reduce the inter-symbol interference. The results of the BER test (section 4.2) confirmed this. However, because of the inherent receiver synchronisation problems, there is some doubt over the validity of these results.

In an attempt to remove this doubt, the received signal phase constellations were extracted from the tape records using Matlab©. Phase Constellation diagrams of the continuous PRBS, with transmit and receive transducers located at nominal depths of 20m and 5m respectively, are shown in Figures 12 and 13, for the ITC-3441 directional hydrophone and the LC10 omni-directional hydrophone. The phase transition table for the 4-DPSK modulator is shown in Table 6. Ideally there should be 4 phasors (each corresponding to a 2-bit sequence or dibit) and hence 4 phase clusters per plot with the degree of spread being an indication of potential errors. In the case of the directional hydrophone, the phase clusters and corresponding demodulated symbols merge and disappear with increased range. In contrast, no phase clusters were obtained with the omni-directional hydrophone and even at the shorter ranges the Matlab© demodulator could not separate the 4 phasors and regenerate the correct symbols. These results follow those of the BER test.

The variations in the corresponding amplitudes of the phase clusters or output signal phasors of the omni-directional and directional hydrophones are caused by the channel, and the fact that the directional hydrophone is 3dB more sensitive on axis than the omni-directional hydrophone. For example, using the measured received carrier signal PSD levels given in Table 4 for a range of 50m, the amplitudes of the output signal phasors of the directional hydrophone should be about 9db (ie.{126-

120}+3) greater than those of the omni-directional hydrophone. At a range of 150m the difference will be about −1dB (ie.{116-120}+3).

Table 6 4-DPSK, Phase transition table

Bit Sequence	Dibit	Phase transition ($\Delta\varphi$)
00	0	0
01	1	$3\pi/2$
10	2	π
11	3	$\pi/2$

4.4 Burst Mode Transmission

The "burst mode" transmission has been successfully used to achieve a high 'burst" data rate in an underwater acoustic channel [8]. The method is claimed to be uniquely suitable for the underwater acoustic channel because most channels are frequency-selective, ie. they have a high bandwidth-timespread product. This type of transmission works on the theory that, if at least two symbols of data can be transmitted and received before the first major multi-path arrival, then these received data symbols should be entirely free of multi-path. If this is the case, then in principle, it should be possible to transfer relatively error free bursts of data without using complex modulation/demodulation and transmit/receiver structure.

For the RDS T2/98 trial, the transmitter was reconfigured to transmit a 1msec burst of all '1' binary data once every second. These times were based on the predicted multi-path delays shown in Figure 4(b) for a 40m deep shallow water channel, with transmit and receive transducers separated in range by 50m and located at nominal depths of 20m and 5m respectively. It was also assumed that the ensuing multi-path signals would decay in less than 1s before the next burst transmission. Figure 4(b) supports this argument.

Unfortunately, the receiver was unable to synchronise to this received signal burst, and it was impossible to obtain a BER versus range measurement. Likewise, the burst is too short to perform any useful offline spectrum analysis because, in 1msec only 16 symbols are transmitted and only 176 samples of received time series data are available for processing. However, samples of the respective omni-directional and directional hydrophone output time series, shown in Figures 14 and 15, clearly show the first major multi-path (SS1) arriving approximately 2.5msec, ie. 2.5E-3x176400 = 441 samples, after the direct path (DP). This agrees well with the predicted multi-path values plotted in Figure 4(b). Figures 14 and 15 also demonstrate the benefit of using a directional hydrophone to reduce the effects of multi-path and noise interference, ie. improve the SNR at the hydrophone output. As shown in Figure 15, the directional hydrophone has, compared to the omni-directional hydrophone output shown in Figure 14, significantly reduced all noise interference and multi-path signals, except the

direct path. The periodic bursts of interference that were unrelated to the burst mode transmission have clearly been attenuated.

4.5 Cepstrum Analysis

According to Randall and Hee [9], cepstrum can be considered to be the spectrum of a logarithmic (amplitude) spectrum. This means that it can be used for detection of any periodic structure in the spectrum, including harmonics, echoes, and in this instance, multi-path. The unique feature of cepstral processing is that it can transform the effect of reflections and echoes having a periodic structure into a simple additive series of delta (ideal reflections only) or impulse response functions [10]. Thus in principle, if the delta or impulse response functions of all multi-path except the direct path (DP) are subtracted from the received signal cepstrum, the resulting cepstrum should be free of multi-path. If the edited cepstrum is then transformed first to the spectrum and secondly into the time signal, then the latter should also be free of multi-path [9]. However, to regenerate the time series and retain the necessary phase and frequency information, the complex cepstrum must be used.

To test this theory, the sequence of operations shown in Figure 16 was simulated in Matlab and applied to a selected sample of recorded time series data. The results obtained without a "lifter" (the cepstrum equivalent of a filter) are respectively shown in Figures 17 and 18 for the directional and omni-directional hydrophones. The results of applying a "'lifter" to the cepstrum of the omni-directional hydrophone data, to zero out the "rahmonics" (the cepstrum equivalent of harmonics) of the major SS1 multi-path component are shown in Figure 19. As previously predicted (refer to Figure 4(b), Tx depth 20m, range 50m), the SS1 rahmonics should, under ideal channel conditions and specular reflection, occur at multiples of 2.5msec

The results (see figure 19), show that applying a coarse "comb-lifter" to zero out the SS1 "rahmonics" from the complex cepstrum, did not improve the demodulated output. In fact, applying a lifter of any sort appeared to make things worse. A similar result was also obtained when the "lifters" were applied to the complex cepstrum of the directional hydrophone data. Further examination showed that the regenerated time series data became worse as more data was "lifted" from the cepstrum. This result suggests that the cepstrum of the direct path signal and that of the major SS1 multi-path overlap. If this is the case, it would be almost impossible to remove the multi-path and leave the direct path cepstrum intact, a point confirmed by Randall and Hee in their discussion of the measurement of the impulse response properties of a reflecting surface [9].

5. Conclusions & Recommendations

The RDS T2/98 UWA Telemetry trial has demonstrated that under near perfect conditions (stationary channel with fixed source and receiver) it is possible to achieve high data rate real-time communication using, differential signalling and simple single path propagation techniques. Using, a relatively simple, low cost, digital UWA telemetry system, a symbol rate of 16kbaud was achieved over ranges up to 100m in a shallow water offshore channel. However, more sophisticated techniques are required to achieve high data rate communication over time varying and band-limited UWA channels. These techniques rely upon the use of more efficient modulation schemes to increase the bandwidth efficiency, joint adaptive equalisation and beamforming to respectively remove the short and long time spread multi-path, and phase tracking methods to ensure tracking of the rapidly changing channel induced phase or Doppler spread.

The time varying nature of the UWA channel was not observed during the trial because of the near perfect conditions. However, the effects of multi-path propagation which cause spreading of the signal in time and space, and respectively appear as frequency and spatial-selective-fading of the signal, were observed from analysis of the recorded data and other channel simulations. Similarly, the spatial and frequency variability of the mean path or transmission loss of the signal was also observed. In normal circumstances the UWA channel is rapidly time varying, and to obtain a more robust communication link it will be necessary to use some or all of the techniques previously discussed.

The effect of surface wave motion, which causes Doppler spreading of the carrier frequency, and manifests itself as fast or short time-selective-fading, has been discussed. However, for reasons given above, it too was not observed during the trial. In time varying channels, where surface wave motion is present and/or the source and receiver are moving, differential demodulation and/or more robust phase-tracking techniques are recommended.

The advantages of using beamforming techniques to remove long time spread multi-path with large or near vertical arrival angles at the receiver, and improve the SNR at the input to the demodulator, have been clearly demonstrated.

A "burst mode" transmission has been demonstrated but because of the shortness of the burst and the inherent receiver synchronisation problems, it was impossible to measure the BER versus range. This mode of transmission works on being able to receive a burst of multi-path free data in the delay time or lag that exists between arrival of the direct and first major multi-paths. Plots of the sampled receive signal generated from recorded trials data certainly confirm that this should be possible, and it is recommended that this method be considered as a future option.

Finally, the application of cepstrum analysis to identify and remove the major multi-paths present in the received acoustic signal and recover the original transmitted signal has been investigated. Initial results suggest that this may not be possible because the cepstrum of the original signal appears to be longer than the lag between the arrival of the direct and first major multi-path. Further investigation is recommended because others have apparently used this method for similar application [11].

6. Acknowledgments

The author would like to thank Mathew Steed for supplying the experimental hardware and helping organise and conduct the trials. In addition the author would also like to thank Messrs Ian Woon and Jarrad Exelby for providing support during and after the trial.

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Appendix A: RDS T1/98 Underwater Acoustic Telemetry Trial Report

The trial objective was to conduct preliminary underwater acoustic telemetry experiments by testing and evaluating the performance of a short range, high data rate, experimental acoustic communication link, in a shallow water off-shore environment. This objective was achieved. All tests, except one, were conducted at Site B, in 20m of water in accordance with the procedure given in Annex D of the Rapidly Deployable Systems RDS T1/98 Local Waters Trials Instruction, Issue1 May 1998. For each test, selected samples of the received time series data were recorded using a 14 channel TEAC XR-510 cassette data recorder, and an HP Signal Analyser was used to monitor and check the power spectrum of the received signal. The BER was not recorded because a Differential QPSK demodulator was not available.

A.1 Records

Tape records of the received time series data were recorded for each short (2m) and medium range (20m) test. The tests were conducted in 20m of water, using a 15msec burst (with a prr of 8sec) and a continuous, (2^{17}-1) bit pseudo random binary transmit pattern with a bit rate of 32,782 bps ie. half the carrier frequency (65564Hz). To accommodate the expected received signal bandwidth (40-90kHz), all tape records were made at 76cm/s, and each lasted for approximately 4 minutes. These are listed in Table A.1. The all '1' binary transmit pattern was introduced towards the end of the trial because it would force the quadrature differential phase shift keyed (4-DPSK) modulator to generate a constant ($\pi/2$) phase shift at each symbol transition. When received and demodulated, this would produce an easily recognisable 4-step staircase type pattern.

The experimental system and trials setup are described in Annex D of the Trials Instruction. However, it should be noted that only one transmit and two frequency compatible receive transducers, an LC10 omni-directional and an in-house purpose built directional transducer designated the "Zebra", were used during the trial. The transmit transducer used was an ITC-2039, Free Flooded Ring, useable frequency range 50-80kHz, resonant frequency 65kHz, and Source Level 175dB re 1μPa rms.

Table A.1 RDST1/98 Underwater Acoustic Telemetry Tape Records

Tape No.	Track No.	Tx Mode	Tx Pattern	Rx Type	Tx/Rx Depth (m)	Tx/Rx Range (m)	Water Depth (m)	Rx Gain Setting (dB)	Recorder I/P Range (V)
1	1	Burst 15mS PRR 8sec	2^17-1 bit PRBS	Zebra	5	over 2	10	+20	0.5
	2	"	"	"	10	2	20	0	1
	3	"	"	"	15	2	20	+20	2
	4	"	"	"	5	2	20	0	0.5
	5	"	"	LC10	5	2	20	+20	2
	6	"	"	"	10	2	20	+20	2
2	1	"	"	"	15	2	20	+20	2
	2	Continuous	"	"	5	2	20	+20	2
	3	"	"	"	10	2	20	+20	2
	4	"	"	"	15	2	20	+20	2
	5	"	"	Zebra	5	2	20	0	0.5
	6	"	"	"	10	2	20	0	0.5
3	1	"	"	"	15	2	20	+20	2
	2	"	"	"	10	20	20	+20	0.5
	3	"	"	"	15	20	20	+20	0.5
	4	"	"	"	5	20	20	+20	0.5
	5	"	"	LC10	5	20	20	+20	0.5
	6	"	"	"	10	20	20	+20	0.5
4	1	"	"	"	15	20	20	+40	5
	2	"	All '1' Binary Sequence	"	15	20	20	+40	2
	3	"	"	"	10	20	20	+40	5
	4	"	"	"	5	20	20	+40	5
	5	"	"	Zebra	10	20	20	+40	5
	6	-	-	-	-	-	-	-	-

Since the trial, wave files have been produced, by replaying each record at 1/8th of the original recording speed ie. 9.5cm/s, and using the PC based sound card to select a 10s time slot from each of the recorded time series. In real time, each wave file corresponds to (10/8)s of real time data, sampled at a rate of (22050 x 8) samples/s, where the sample rate of the sound card was 22050 samples/s. These files are stored at I:\rds\T1_98\Tape#\Track_#.wav, and can be read by using the matlab wavread command.

A.2 Results

A.1.1. Short Range Tests

The main aim of the short range test was to establish a reliable underwater acoustic telemetry link in a relative free-field environment. This was achieved by placing the transmit and receive transducers 2m apart and initially positioning them at mid-water depth to ensure that the direct path dominated and the effects of multi-path propagation, that cause spreading of the transmitted signal in time, frequency, and space, were minimised. Without the 4-DPSK demodulator fitted, we were not able to measure the BER of the received signal (see Figure A.1), however, as expected, there was no sign of any multi-path effects ie. time-selective or frequency-selective-fading.

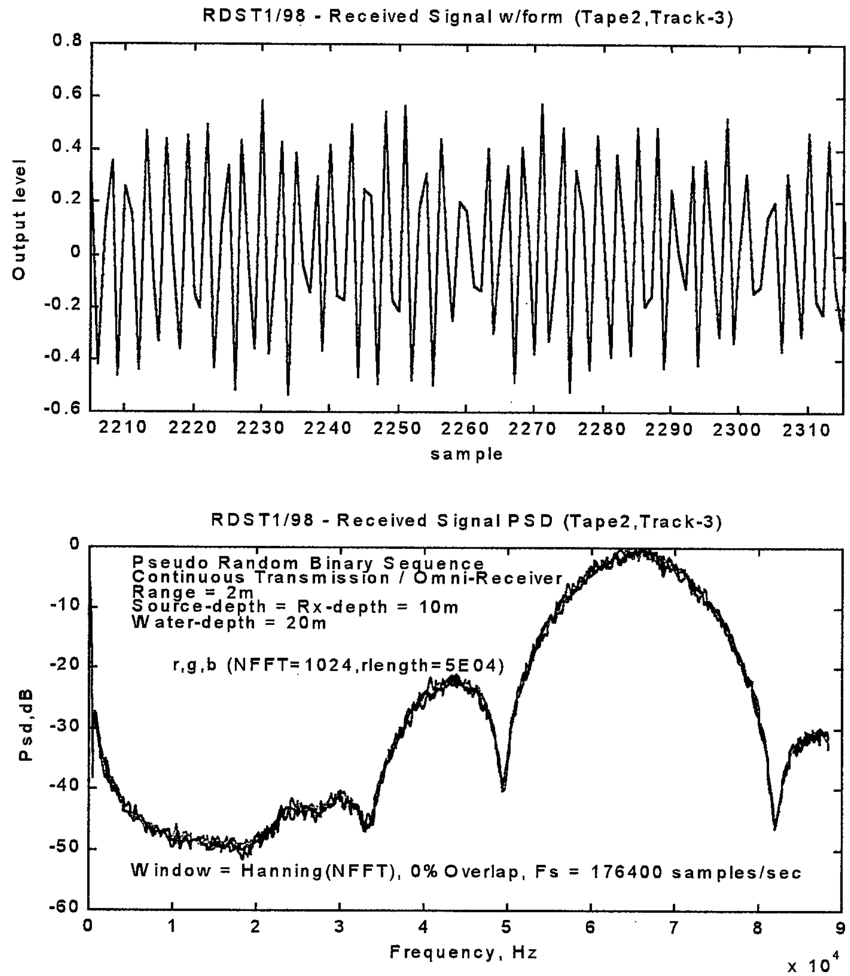


Figure A.1 Short Range Acoustic test, PRBS, sample received signal waveform & PSD.

The received signal waveform shown in Figure A.1 is the sampled version of the realtime received signal waveform, sampled at an effective sample rate of (22050x8) samples/s.

receiving transducer and a 1024 point FFT with a Hanning window, 0% overlap, and a 50k point sample. What these plots show is that over the combined duration of these time slots, ie. (3x283ms), the received signal PSD did not change, proving that the acoustic channel was time invariant and not fast fading.

No attempt was made to look for any multi-path angle spread ie. space-selective-fading, because of the difficulty in moving and accurately positioning the receiving transducer relative to the transmitting transducer and the short range between the two transducers. Besides, both receiving transducers, the LC10 omni-directional and the "zebra" directional, were single output devices.

To investigate the effects of multi-path propagation, particularly the delay spread that supposedly produces frequency-dependent gains and phase shifts across the signal band ie. frequency-selective-fading, the short range tests were repeated with the transmit and receive transducers at (¼) and (¾) water depth. The tests were conducted using both burst and continuous transmissions. The result for the continuous transmission, with the LC10 receiving transducer, is shown in Figure A.2. This intuitively was expected to provide a worst case scenario, but as previously found with the directional hydrophone, there was no significant difference in the received signal PSD, at the three tx/rx depth settings.

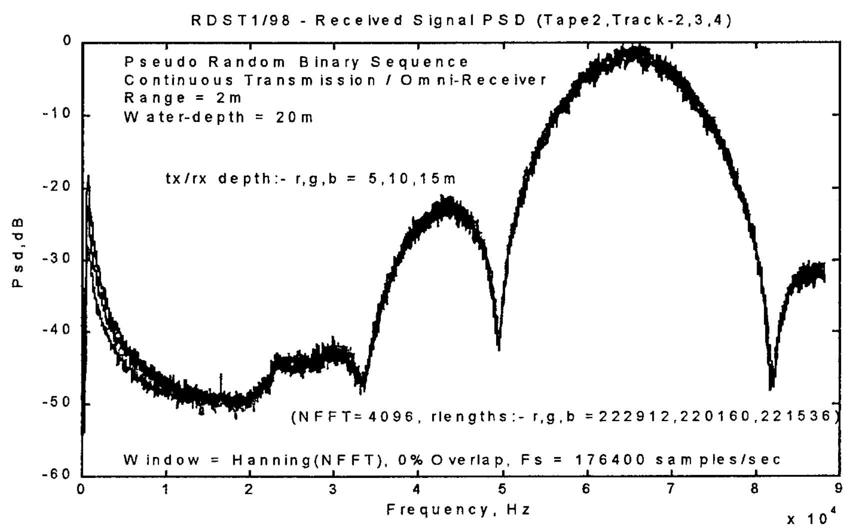


Figure A.2 Short Range Acoustic test, PRBS, received signal PSD vs depth

The effect of surface motion on the doppler spreading of the signal is considered by other researchers to be a major source of temporal variability in shallow water, and manifests itself as fast or time-selective-fading. However, during these tests the sea surface was almost flat ie. SS0-SS1, and this effect was not observed.

A.1.2. Medium Range Tests

The main aim of the medium range tests, was to attempt to deliberately degrade the performance of the short range underwater acoustic telemetry link so that the effects of multi-path propagation would become more dominant and easier to observe. This was done, by using a continuous transmission with transmit and receive transducers spaced 20m apart and initially placed at mid-water depth ie. 10m. As before, without the 4-DPSK demodulator we were not able to measure the BER however, the received signal PSD (Figure A.3), surprisingly showed little evidence of any multi-path effects, particularly delay spread, which as previously mentioned produces frequency-selective-fading across the signal band. In hindsight, this result may be explained by the fact that for this test the surface and bottom reflected paths could have cancelled because the acoustic set up was perfectly symmetrical ie. the surface was flat, the bottom was low absorptive sand, and the acoustic axes of the transmit and receive transducers were aligned at mid-water depth.

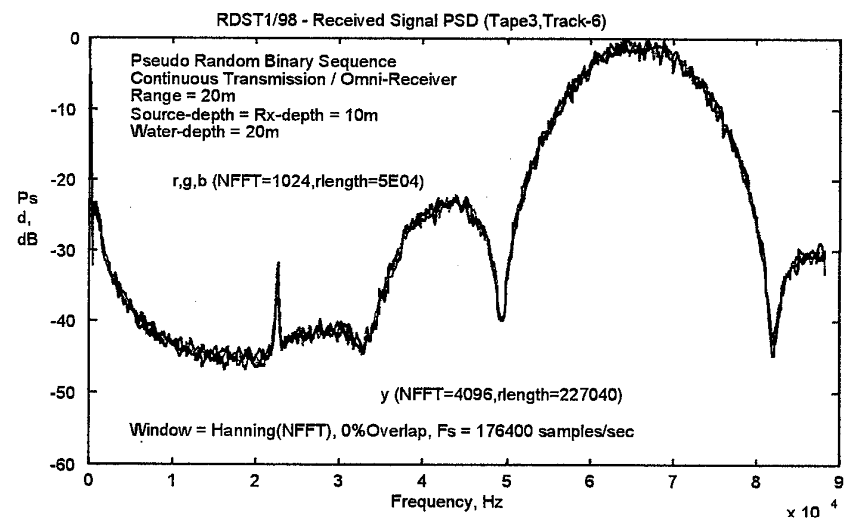


Figure A.3 Medium Range Acoustic Test, PRBS, mid-water depth, omni receiver

For the test set up used, the *Channel-Coherence-Bandwidth,* which is defined to be the inverse of the multi-path delay spread, was calculated to be about 180Hz, ie. (1/delay spread) where the delay spread was estimated to be 5.5ms. The yellow curve shown in Figure A.3 is a plot of the received signal PSD obtained using a 4096 point FFT with a Hanning window, 0% overlap, and a total record length of rlength samples. Once again, there is no evidence of frequency-selective-fading or drop outs.

The red, green, and blue plots shown in Figure A.3, are the averaged received signal PSD of 3 consecutive 283ms time slots obtained using a 1024 point FFT with a Hanning window, 0% overlap, and a 50k point sample. Again, the received signal PSD was

constant over the 3 x 283ms time slot, proof that the acoustic channel remained time invariant and was not fast fading.

In a further attempt to degrade the telemetry link performance and expose the effects of multi-path propagation, particularly the delay spread, the medium range tests were repeated with the acoustic axes of the transmit and receive transducers aligned at (¼) and (¾) water depth. To obtain a worst case scenario, all tests were conducted using continuous transmissions. The averaged received signal PSD recorded using an LC10, omni-directional, receiving transducer, at each test depth, are shown in Figures A.4 and A.5. As before, the red, green, and blue plots are the averaged received signal PSD of 3 consecutive 283ms time slots obtained using a 1024 point FFT with a Hanning window, 0% overlap, and 50k point sample. Likewise, the yellow curve, is a plot of the received signal PSD obtained using a 4096 point FFT with a Hanning window, 0% overlap, and the total record length ie. rlength samples.

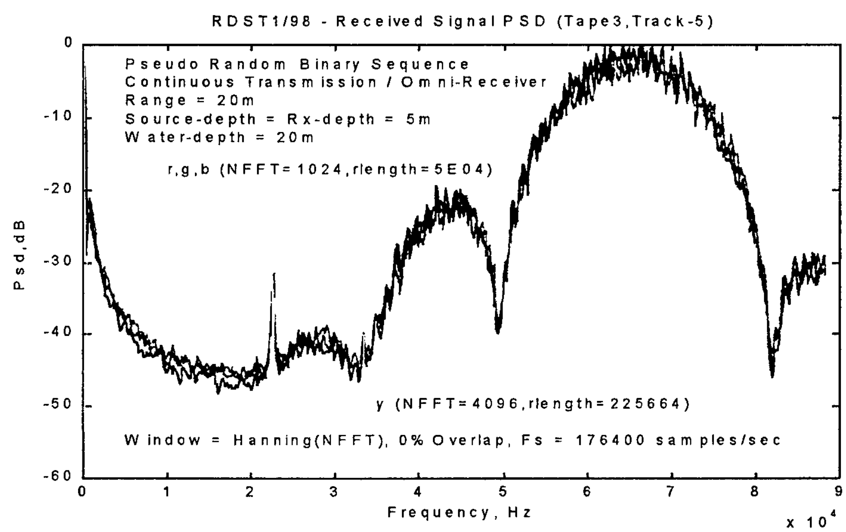


Figure A.4 Medium Range Acoustic Test, PRBS, ¼ water depth, omni receiver

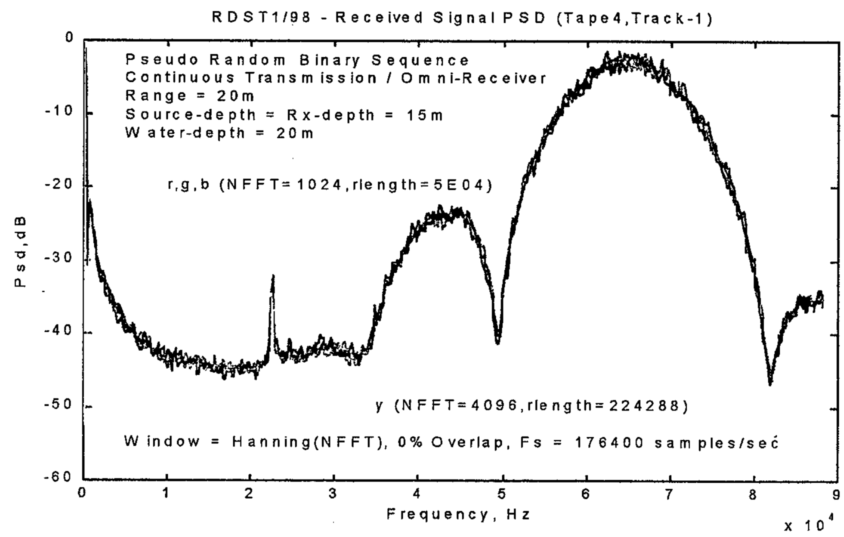


Figure A.5 Medium Range Acoustic Test, PRBS, ¾ water depth, omni receiver

As the red, green, and blue plots in Figures A.4 and A.5 show, the received signal PSD did not change over the duration of the 3 consecutive time slots, proving that the acoustic channel was essentially time invariant and not fast fading. This was to be expected because the sea surface was flat. Likewise, there appears to be no significant evidence of dropouts or frequency-selective-fading. However, if we ignore the effects of normalisation of the respective PSD shown on figures A.3, A.4, and A.5, then it is noticeable that the variance in the respective PSD plots does increase as the acoustic axes of the transducers are moved closer to the surface. This would, as expected, indicate that the surface reflected signal causes more interference to the direct path as the path difference between the two decreases and the influence of the bottom reflected path is reduced. Conversely, moving the acoustic axes of the transducers closer to the bottom has reduced the effect of the surface reflected path, but increases, to a lesser amount, the effect of the bottom reflected path.

The effect of multi-path angle spread ie. space-selective-fading, was investigated by comparing the received PSD plots of the LC10 omni-directional shown in Figure A.3 with those obtained using the 'zebra' directional receiving transducer shown in Figure A.6. In each case, the acoustic axes of both transducers were aligned at mid-water depth. Although there appears to be little difference between the two figures, the signal component seen at about 1/3 of the carrier frequency with the LC10 omni-directional hydrophone is not present with the directional transducer/hydrophone. It is important to note that the directional/spatial response of the zebra transducer has not been accurately measured. However, it does have a max/min response along its acoustic/vertical axes, which would provide some spatial filtering, particularly in the near vertical direction.

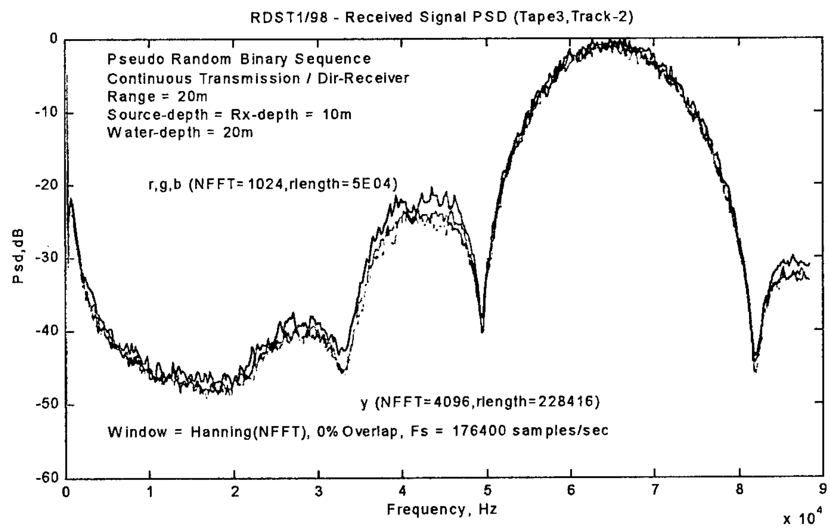


Figure A.6 Medium Range Acoustic Test, PRBS, mid-water depth, directional receiver

Results of the continuous all '1' binary transmit pattern tests conducted, with the transmit and receive transducers aligned at ¼, ½, ¾ water depth, are shown in Figures A.7, A.8, A.9. In each case the phase demodulated data correctly steps through the 4 corresponding phases or symbol states at a symbol rate of about 16ksps (actually 65564/4 = 16391sps). Once again, it is noticeable that the variance in the respective "all ones" phase demodulated data plots does increase as the acoustic axes of the transducers are moved closer to the surface. Likewise, if the mid-water demodulated data plots of the omni-receiver (Figure A.8) and directional-receiver (FigureA.10) are compared, the latter does appear to be cleaner, suggesting that the directional receiver does help by providing some spatial filtering.

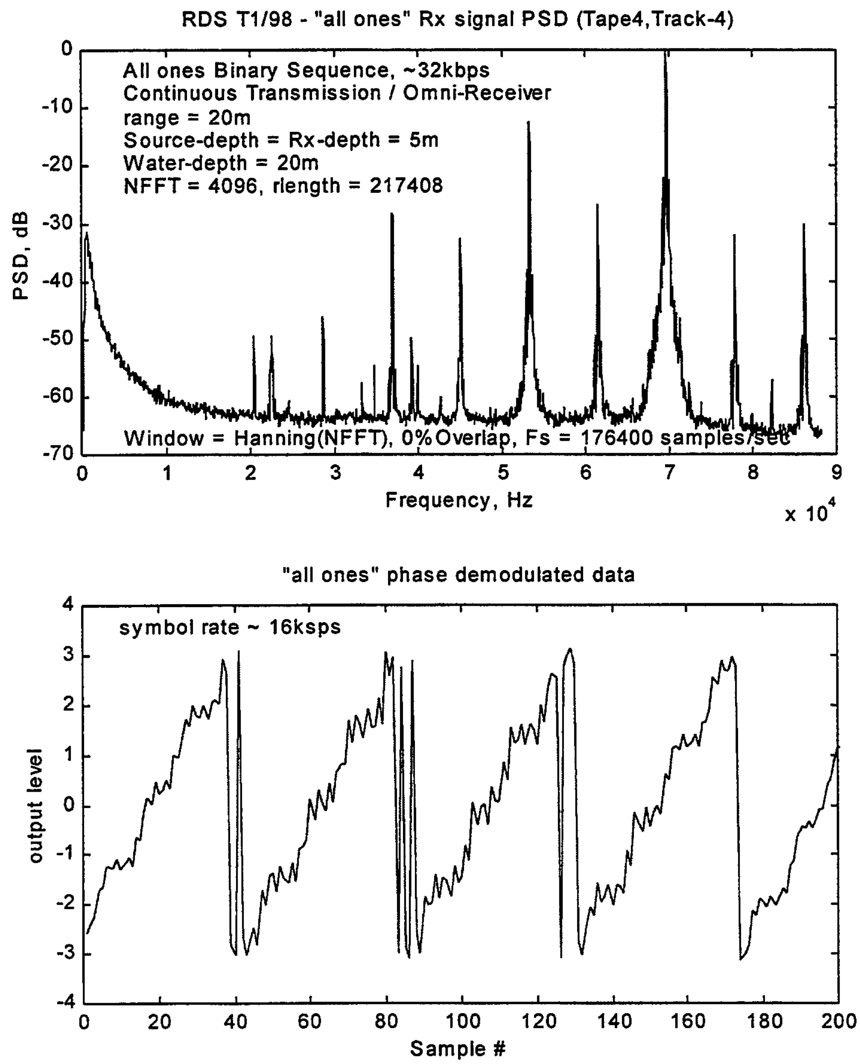


Figure A.7 Medium Range Acoustic Test, all ones data, ¼ water depth, omni receiver

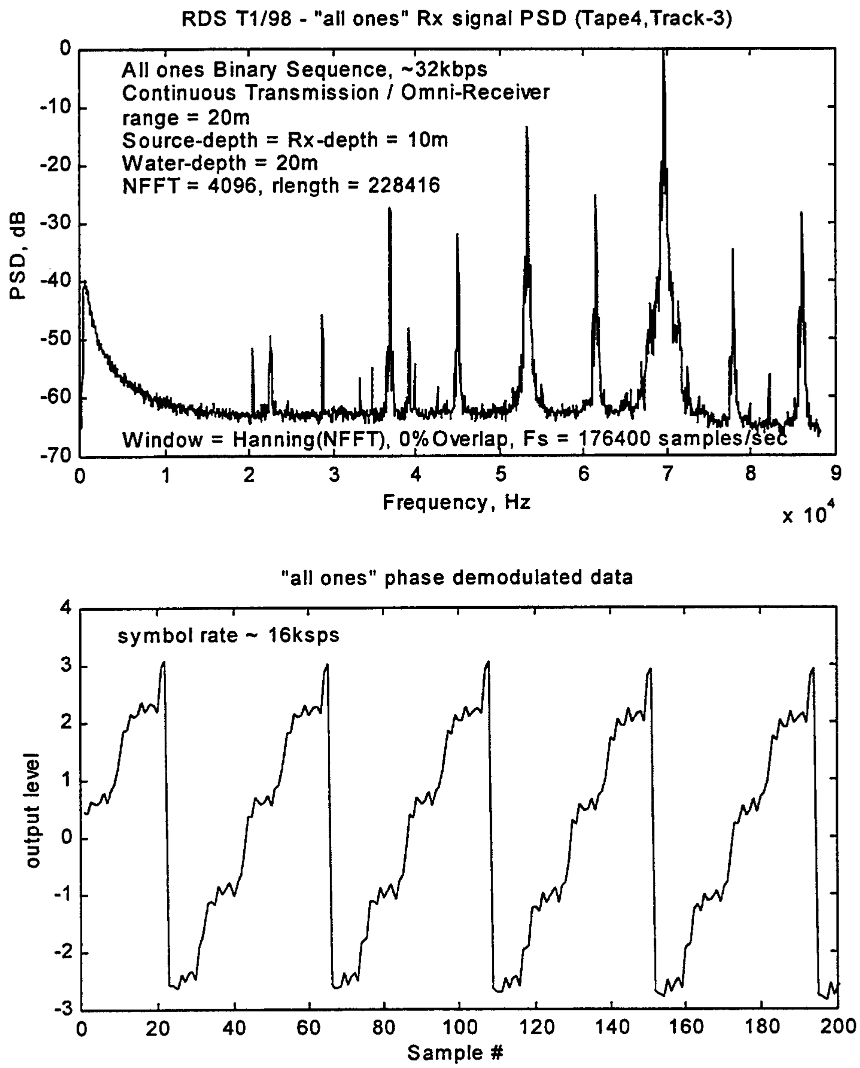


Figure A.8 Medium Range Acoustic Test, all ones data, ½ water depth, omni receiver

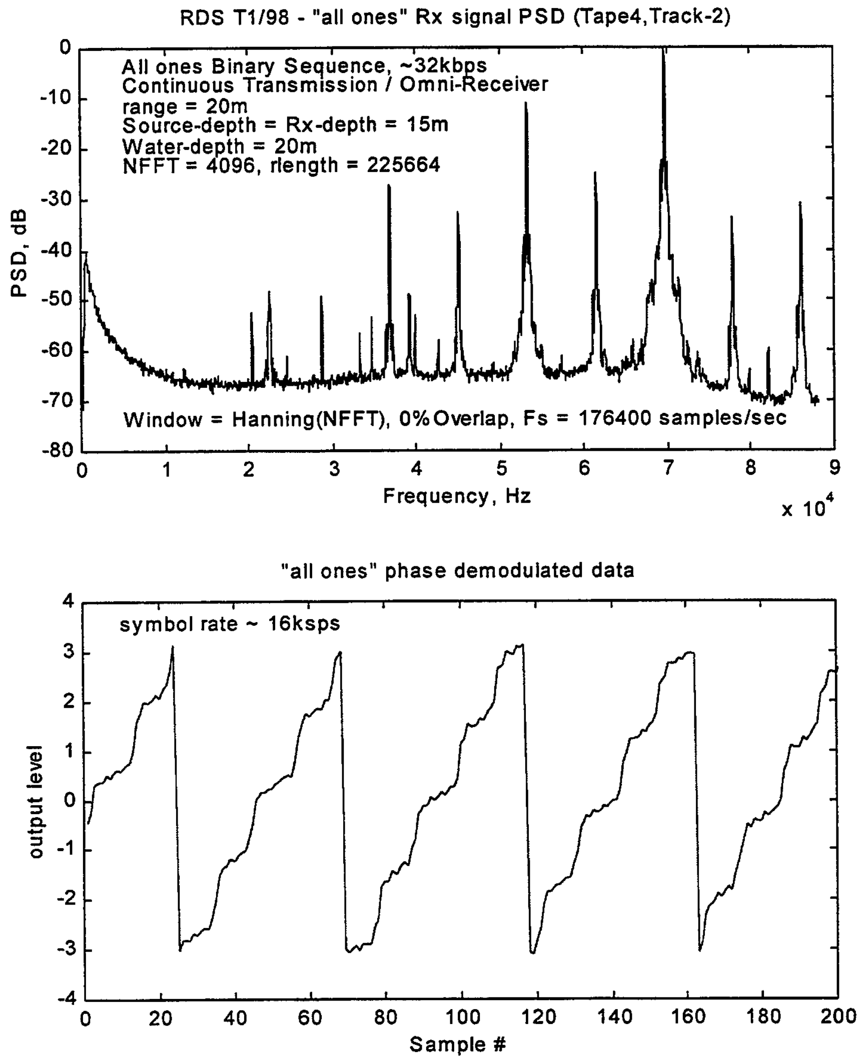
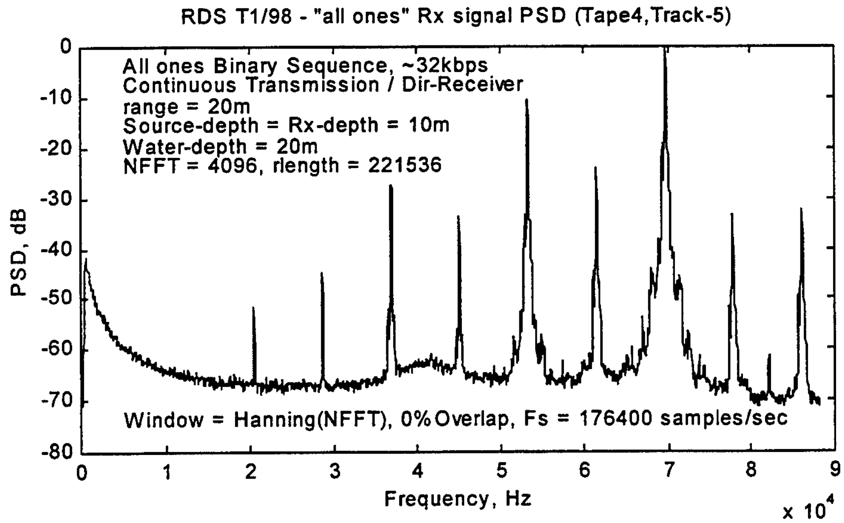


Figure A.9 Medium Range Acoustic Test, all ones data, ¾ water depth, omni receiver



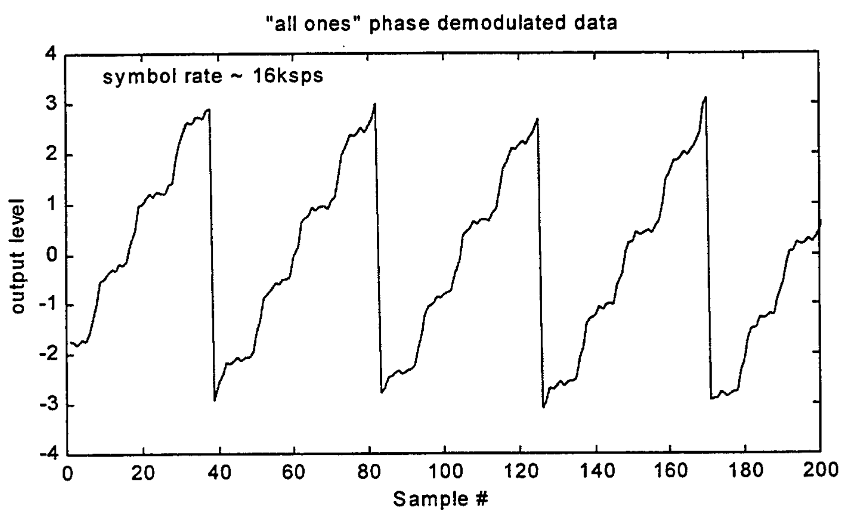


Figure A.10 Medium Range Acoustic Test, all ones data, ½ water depth, directional receiver

A.3 Conclusions

1) The RDST1/98 Acoustic Telemetry Experiments were successfully completed in accordance with the procedures given in Annex D of the trial instruction. All experiments, except one, were conducted at Site B in 20m of water.

2) A wide-band (40-90kHz), high speed (~32kbps), underwater experimental acoustic telemetry link, using a 4-DPSK modulation scheme has been successfully tested in 20m of water over distances of 2m and 20m and depths of ¼, ½, and ¾ water depth. Two data sources were used, a (2^{17}-1) PRBS and an all '1' binary sequence. The BER was not measured during the trail because the 4-DPSK demodulator was not functional, however this has now been fixed and will be available for the following RDST2/98 trial.

3) The effects of multi-path propagation that cause spreading of the acoustic signal in time, frequency, and space were not significant at these short ranges. In particular :-

   - the sea surface was predominantly flat for most of the trial, and there was little or no surface induced doppler spreading. Hence, there was no real evidence of time-selective or fast fading and the channel was predominantly time invariant.

   - the effect of multi-path delay spread, which is the cause of frequency-selective-fading in shallow water channels, was not observed at either of the ½ and ¾ water depth test settings. However, at the ¼ water depth setting, there was a noticeable increase in the variance of the received and phase demodulated signals as the influence of the surface (macro-multi) path on the direct path, was increased.

4) The advantage of using a directional hydrophone to provide single-path-propagation and combat multi-path, has been demonstrated.

A.4 Recommendations

1) The RDST2/98 Acoustic Telemetry Experiments be planned to better :-

   - highlight the effects of multi-path propagation by operating close to the surface in sea state greater than 1 and at ranges greater than 20m.

   - demonstrate the advantage of using a directional hydrophone to provide single-path-propagation, and help combat the effects of multi-path.

2) To provide a measure of the link performance, a BER test should accompany all future acoustic telemetry experiments

A.5 Acknowledgements

Messrs Matthew Steed and Ian Woon for supplying the relevant test hardware, and support during and after the trial.

R.Alksne

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Undersea Surveillance Technology

Maritime Operations Division Salisbury

July 98

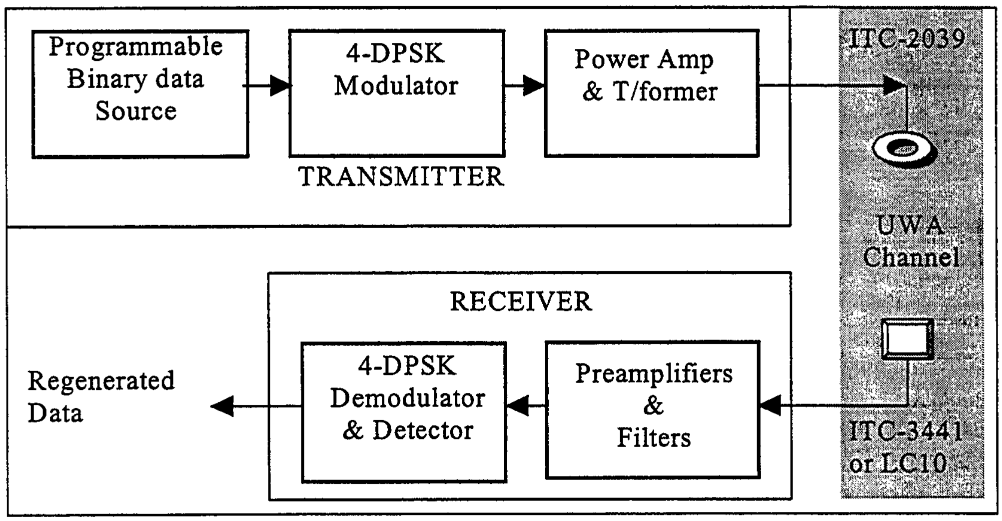


Figure 1   Experimental UWA Telemetry System, schematic

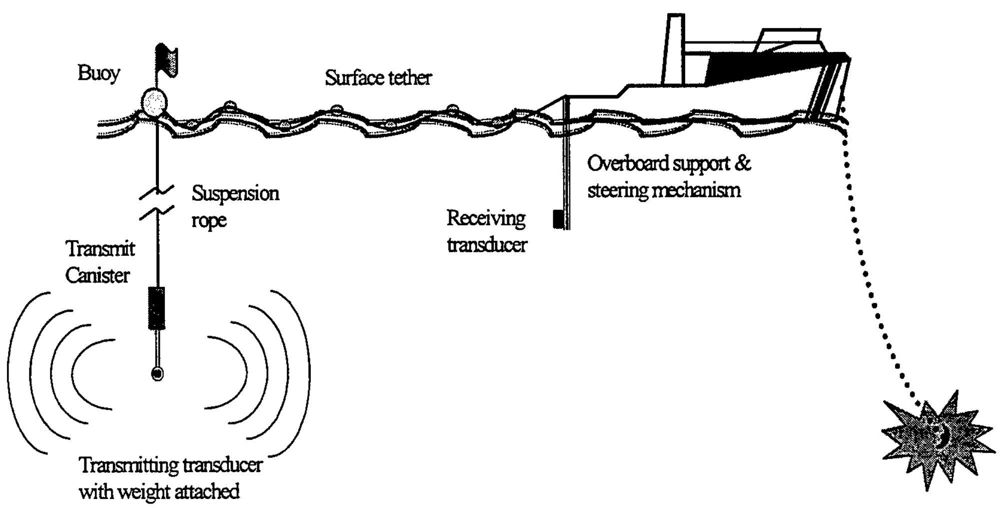
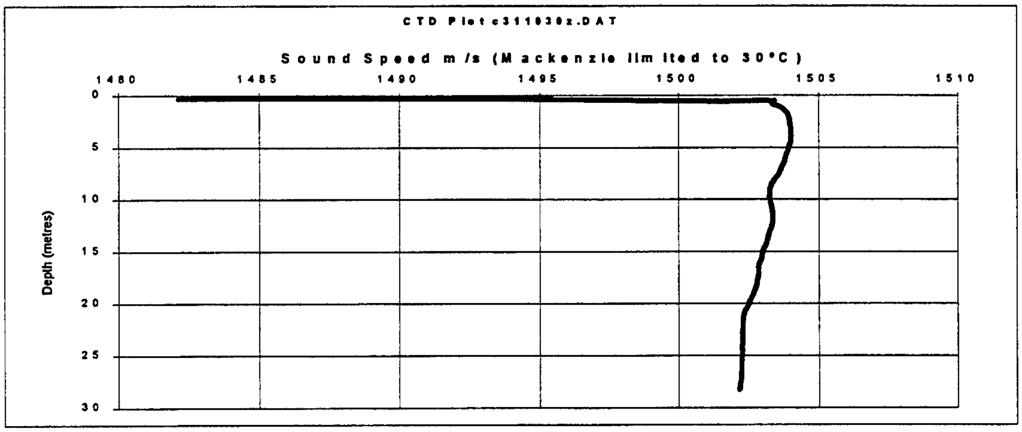
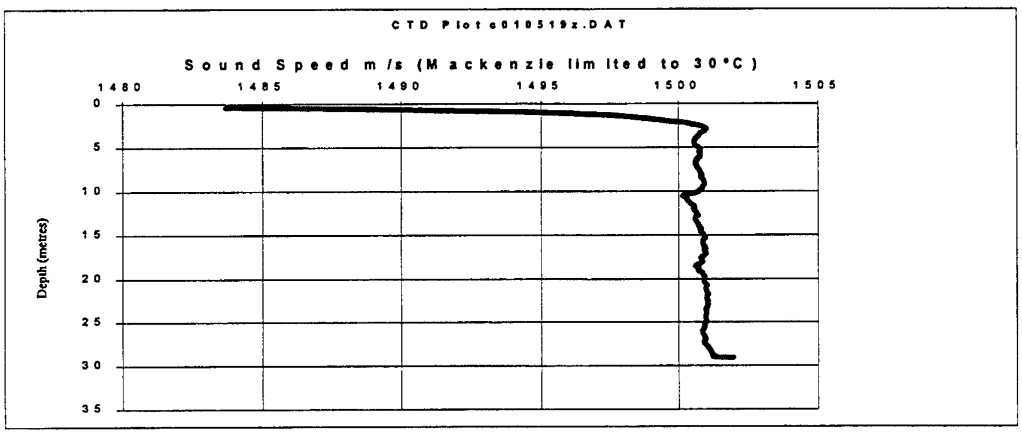


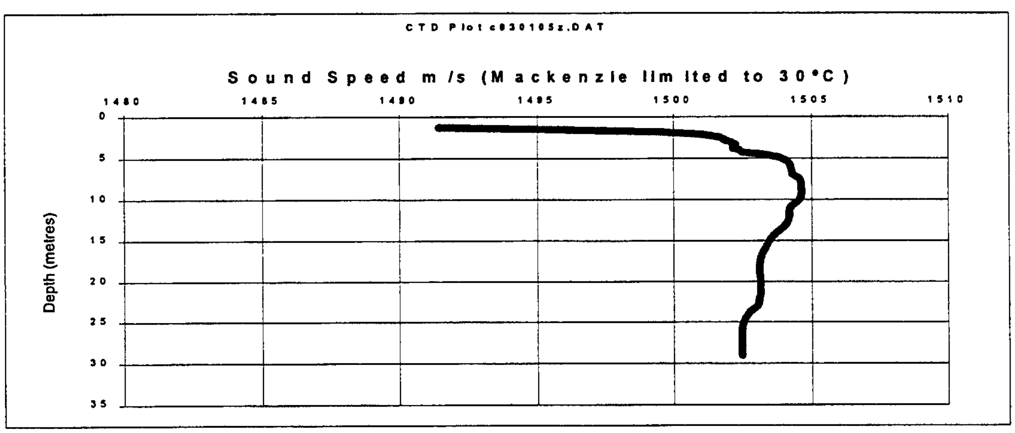
Figure 2   RDS T2/98 Experimental UWA Telemetry trials set up



(a) Sound speed Profile, Site A, 31Aug98, 2000hrs CST

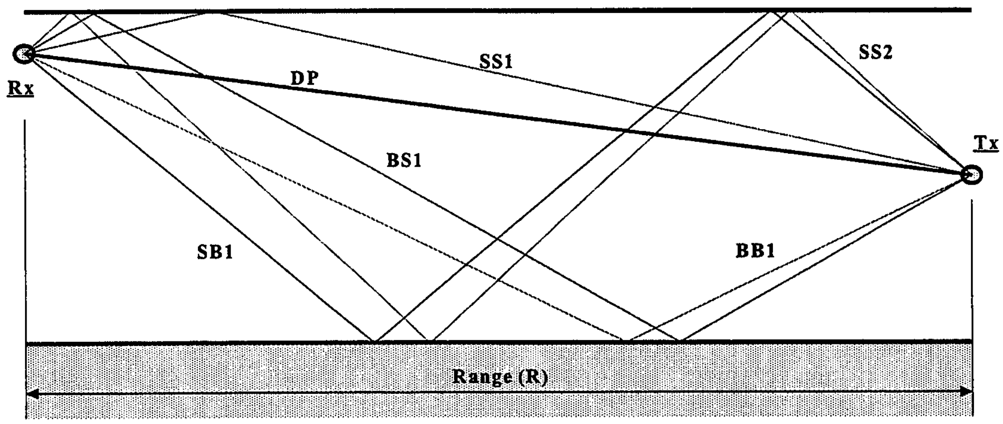


(b) Sound Speed Profile, Site A, 1Sept98, 1439hrs CST

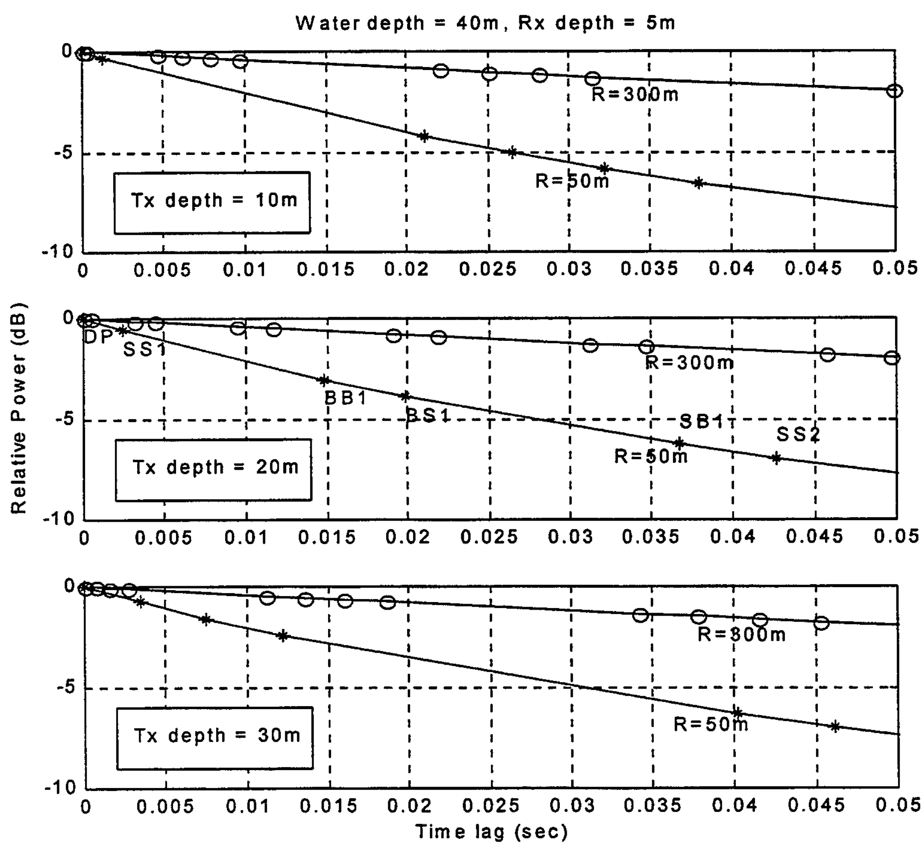


(c) Sound Speed Profile, Site A, 3Sept98, 1035hrs CST

Figure 3 *RDS T2/98 Site Sound Speed Profiles*



(a) Multi-path Model



(b) RDS T2/98 Predicted Multi-path versus Tx depth

Figure 4 *RDS T2/98 Multi-path Modelling*

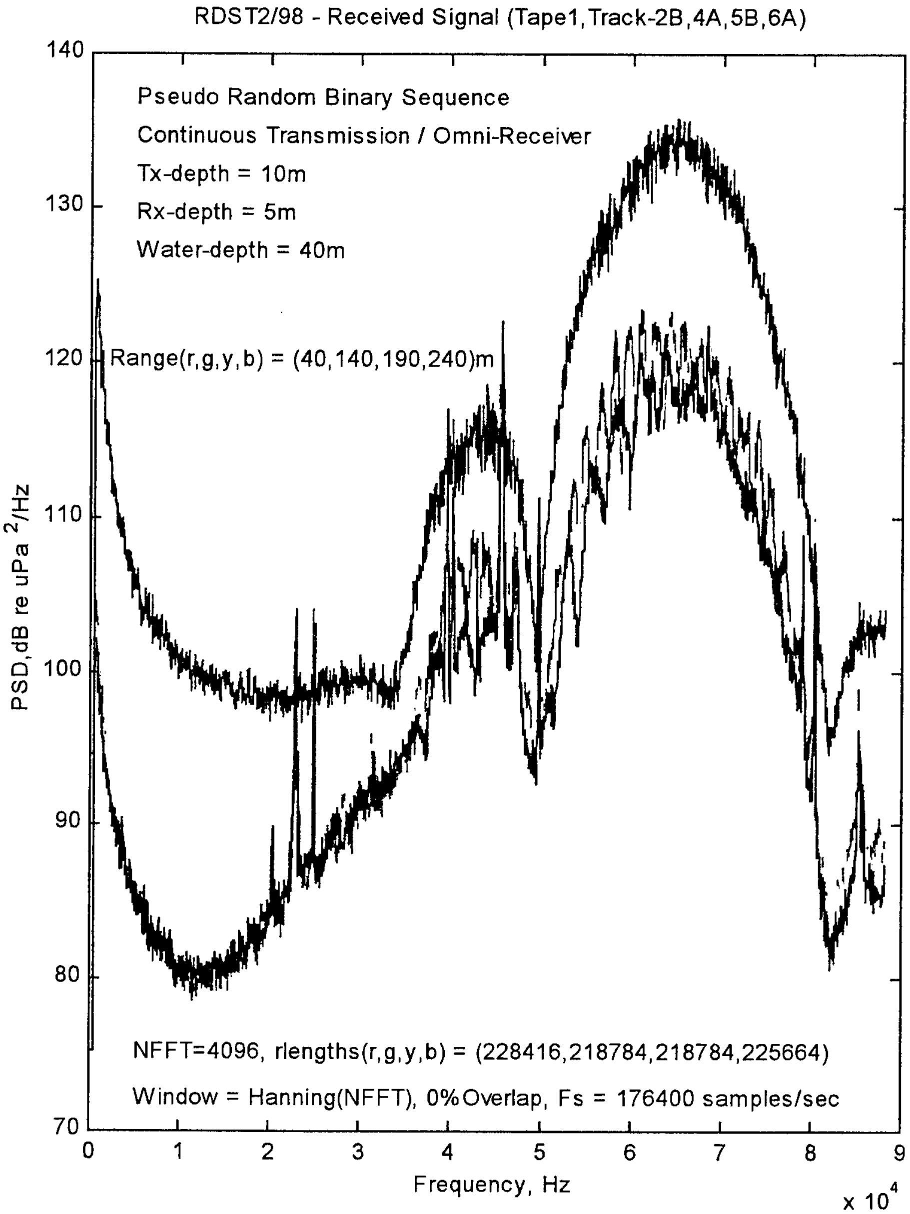


Figure 5 *Received signal PSD versus frequency for different ranges, LC10 hydrophone, Tx-depth = 10m*

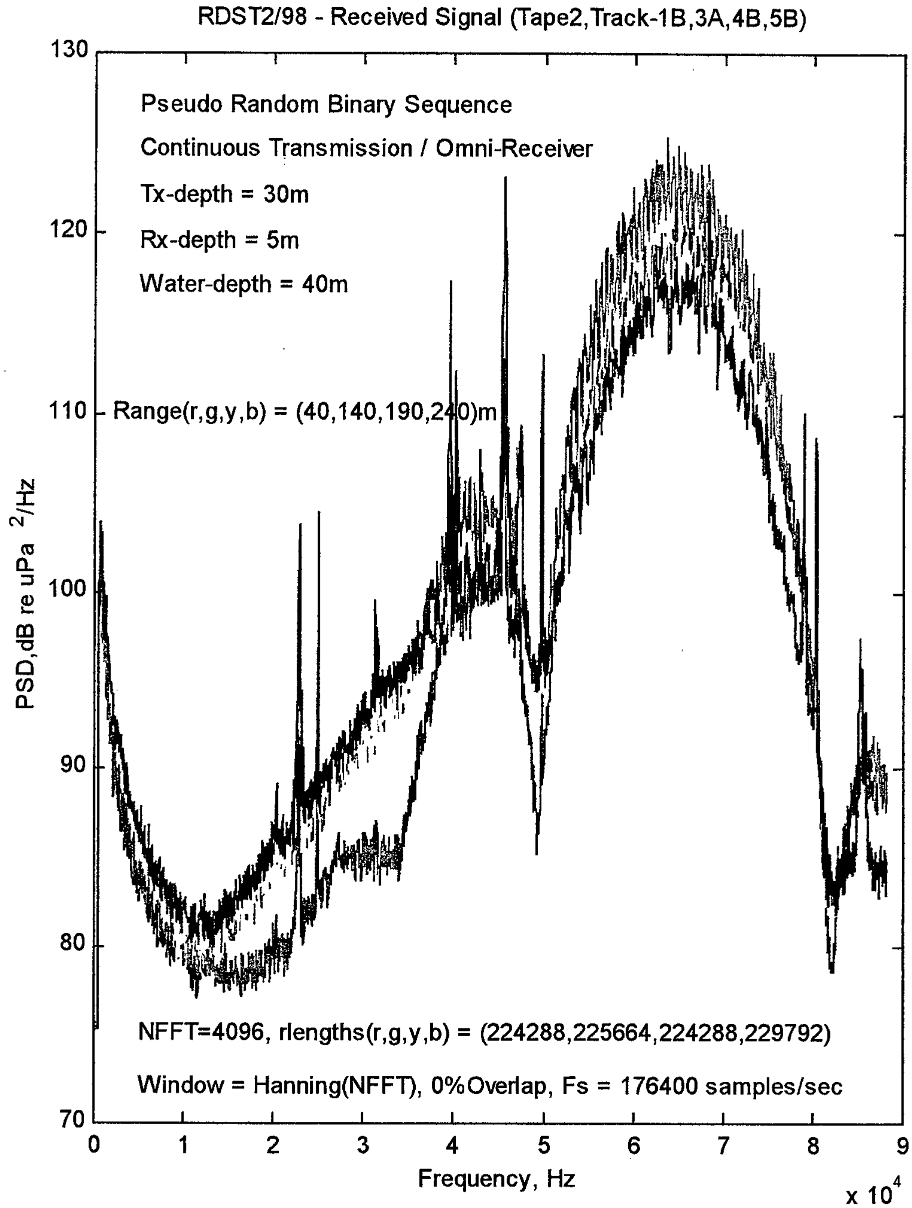


Figure 6 *Received signal PSD versus frequency for different ranges, LC10 hydrophone, Tx-depth = 30m*

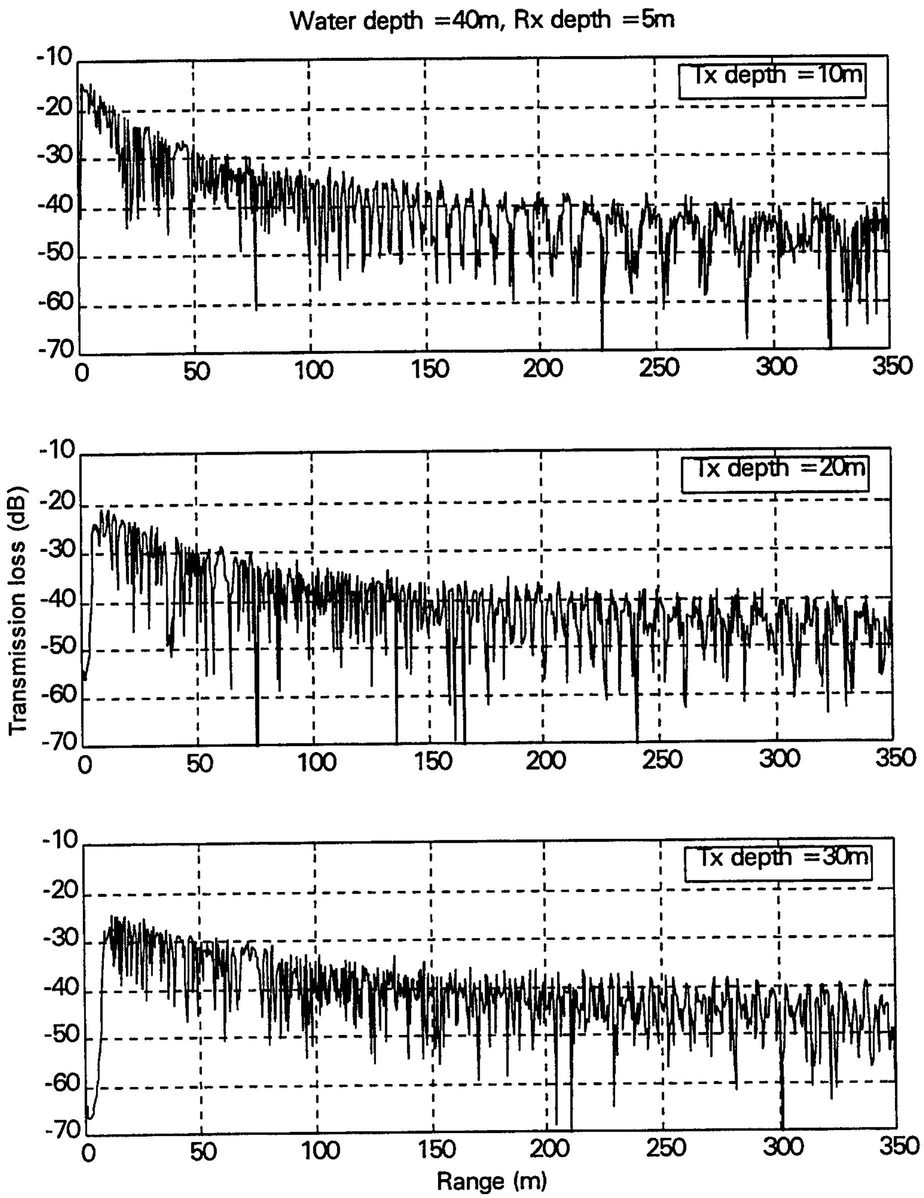


Figure 7 RDS T2/98 KRAKENC Predictions versus range for different Tx depths

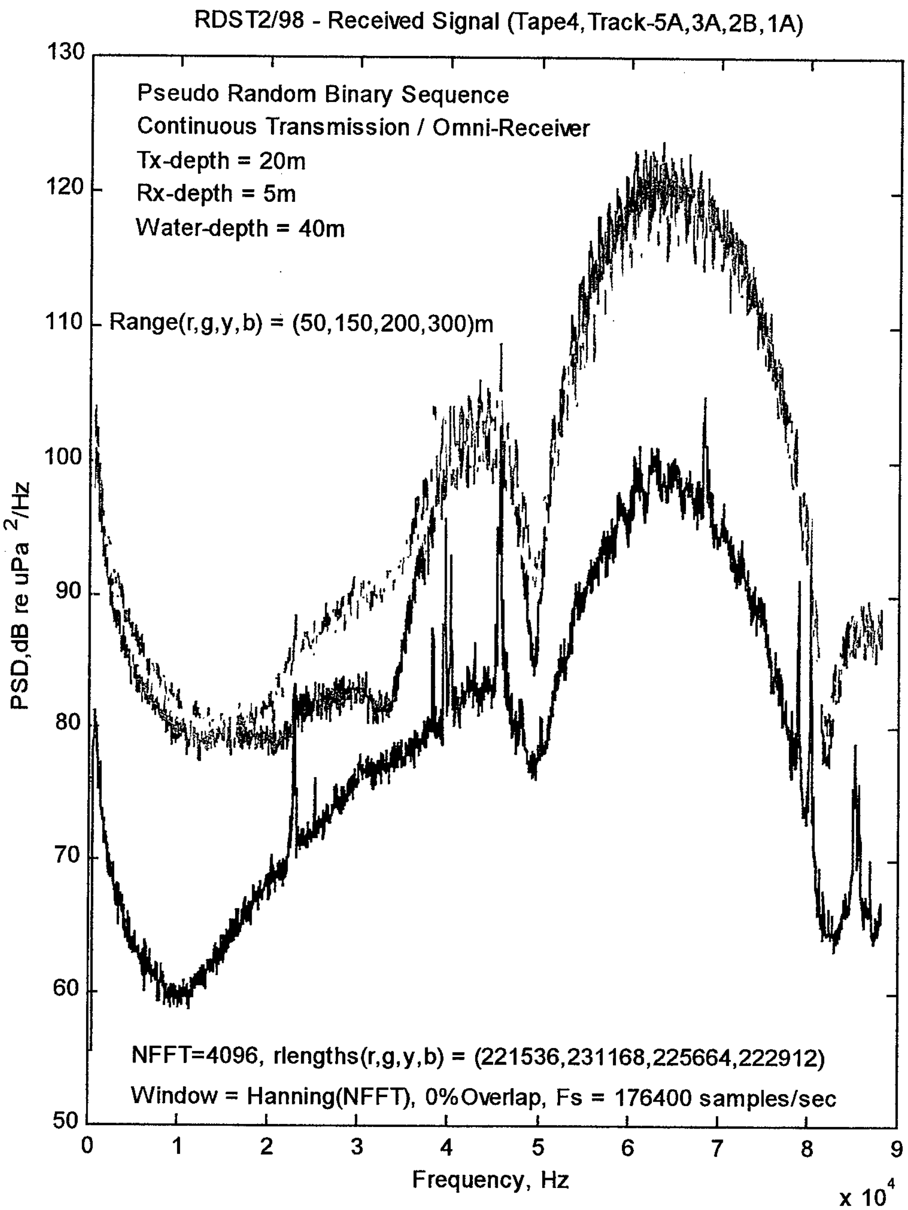


Figure 8 *Received signal PSD versus frequency for different ranges, LC-10 hydrophone*

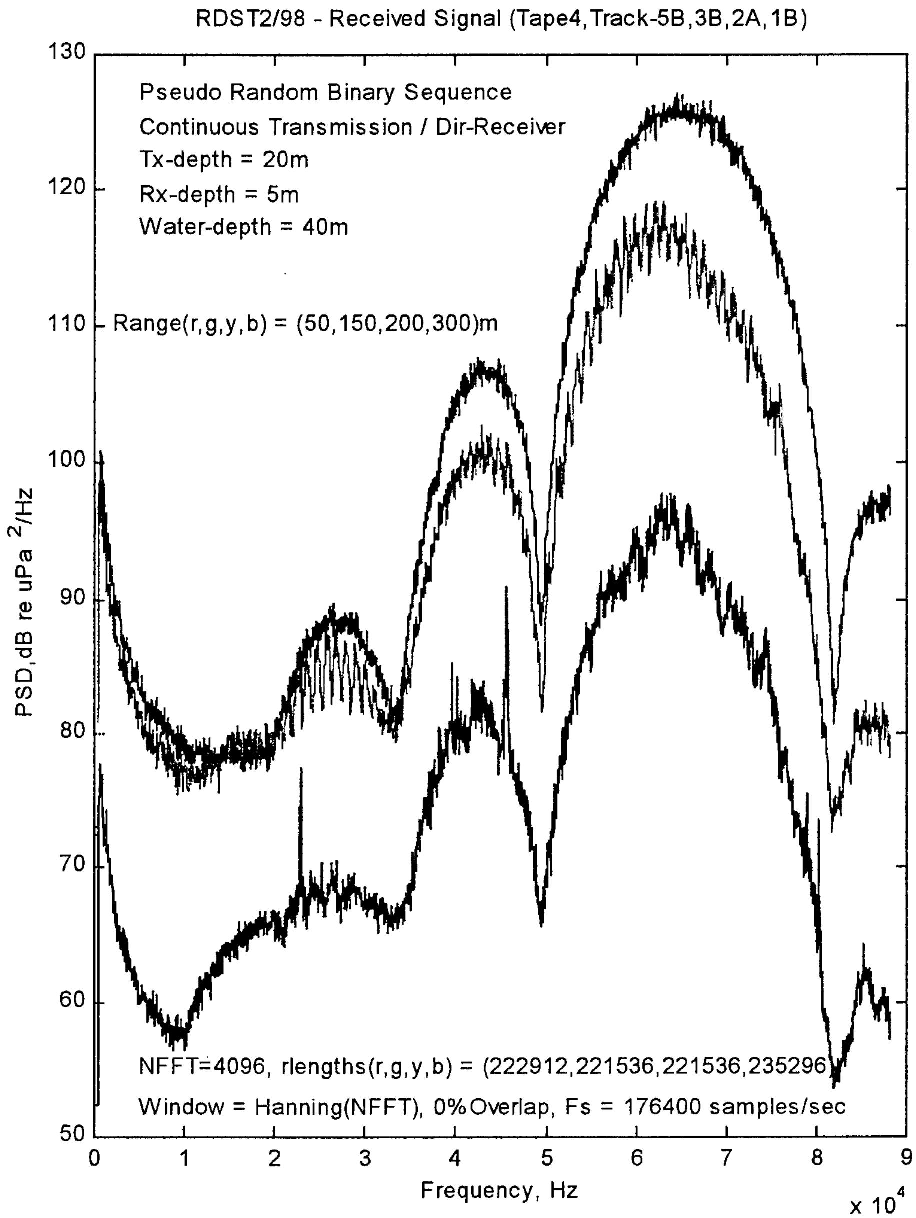


Figure 9 Received signal PSD versus frequency for different ranges, ITC-3441 hydrophone

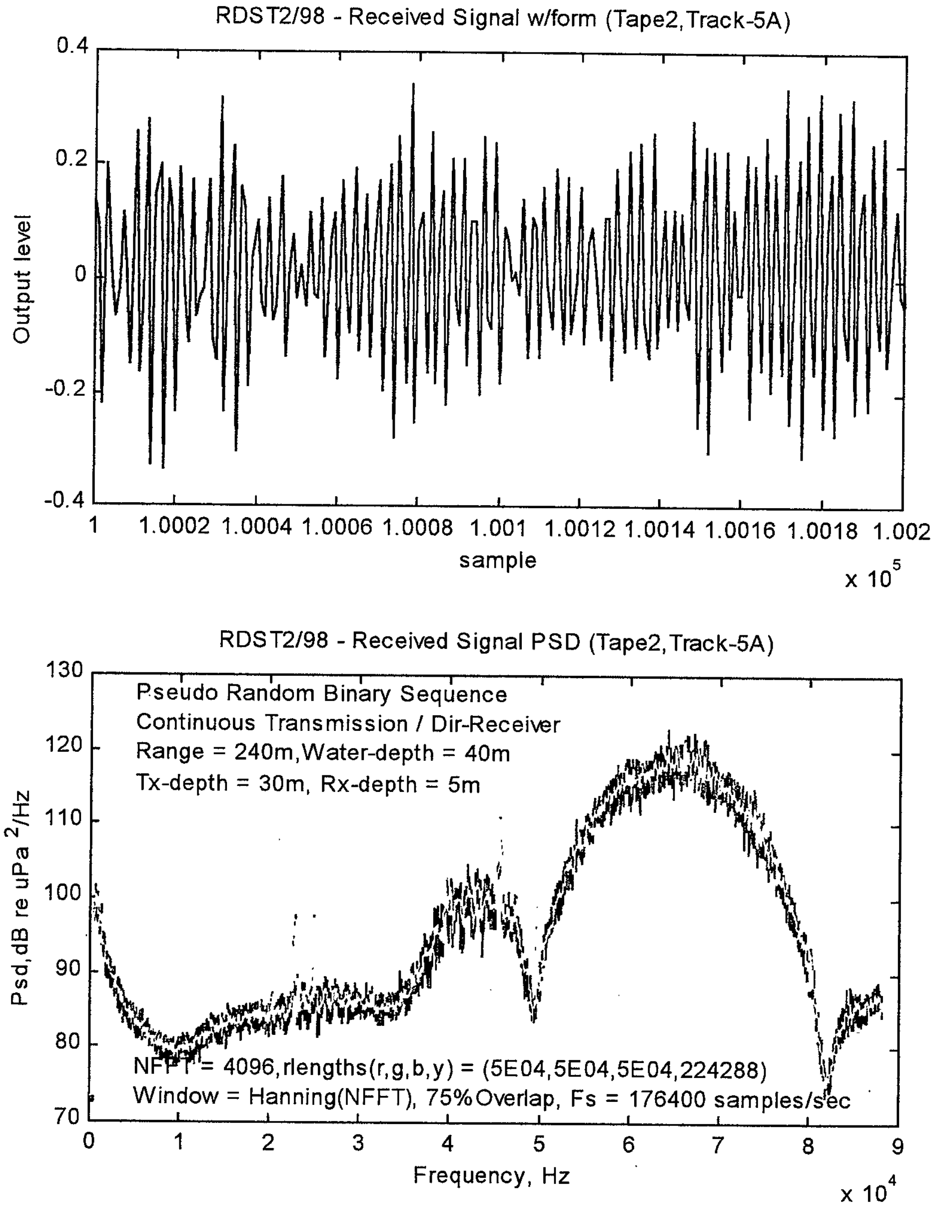


Figure 10 Received signal waveform versus time & PSD, ITC-3441 hydrophone

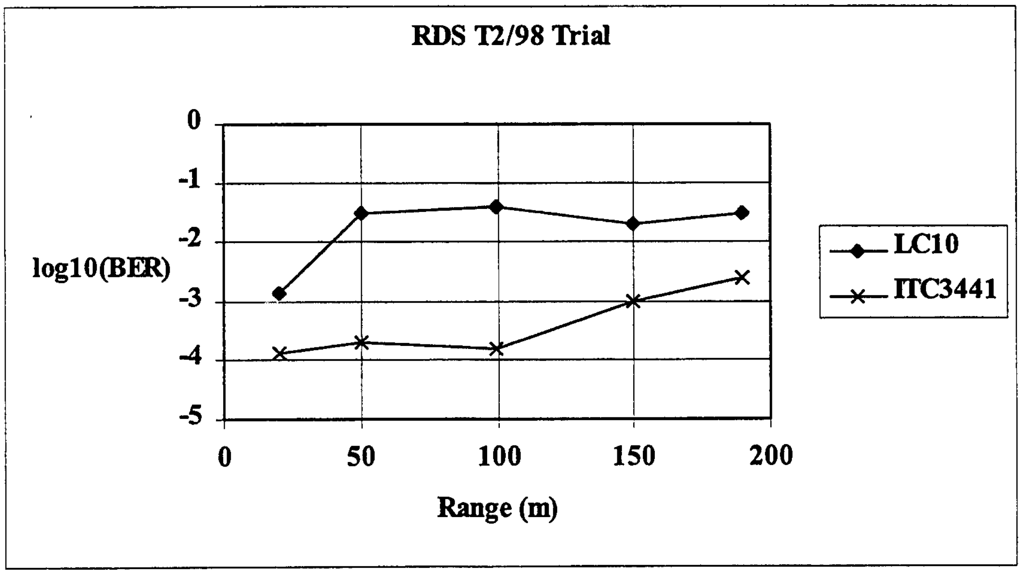


Figure 11 *RDS T2/98 BER versus range (LC10 Omnidirectional & ITC-3441 Directional Hydrophones)*

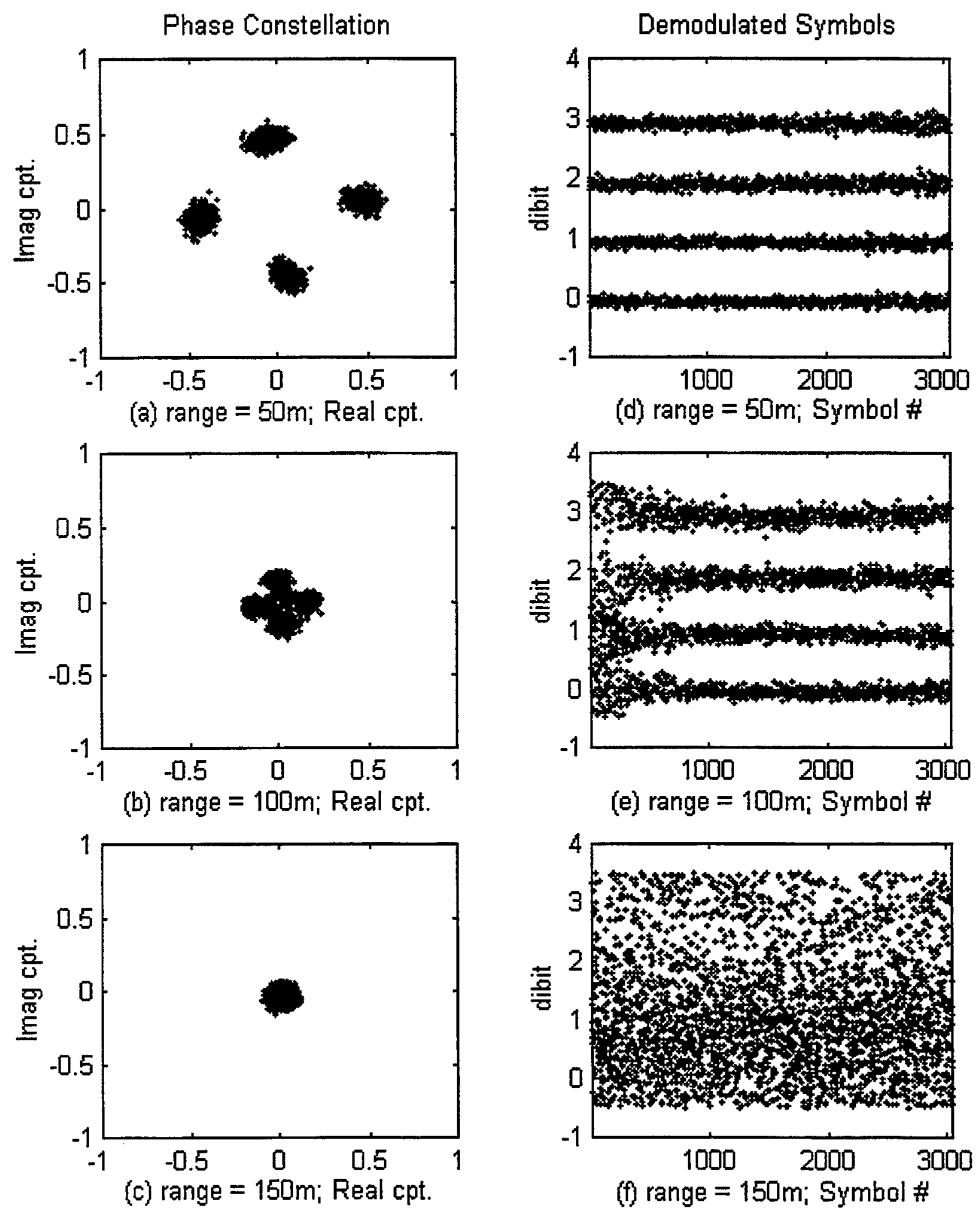


Figure 12 ITC-3441 hydrophone, received signal constellations (rx-depth=5m, tx-depth=20m)

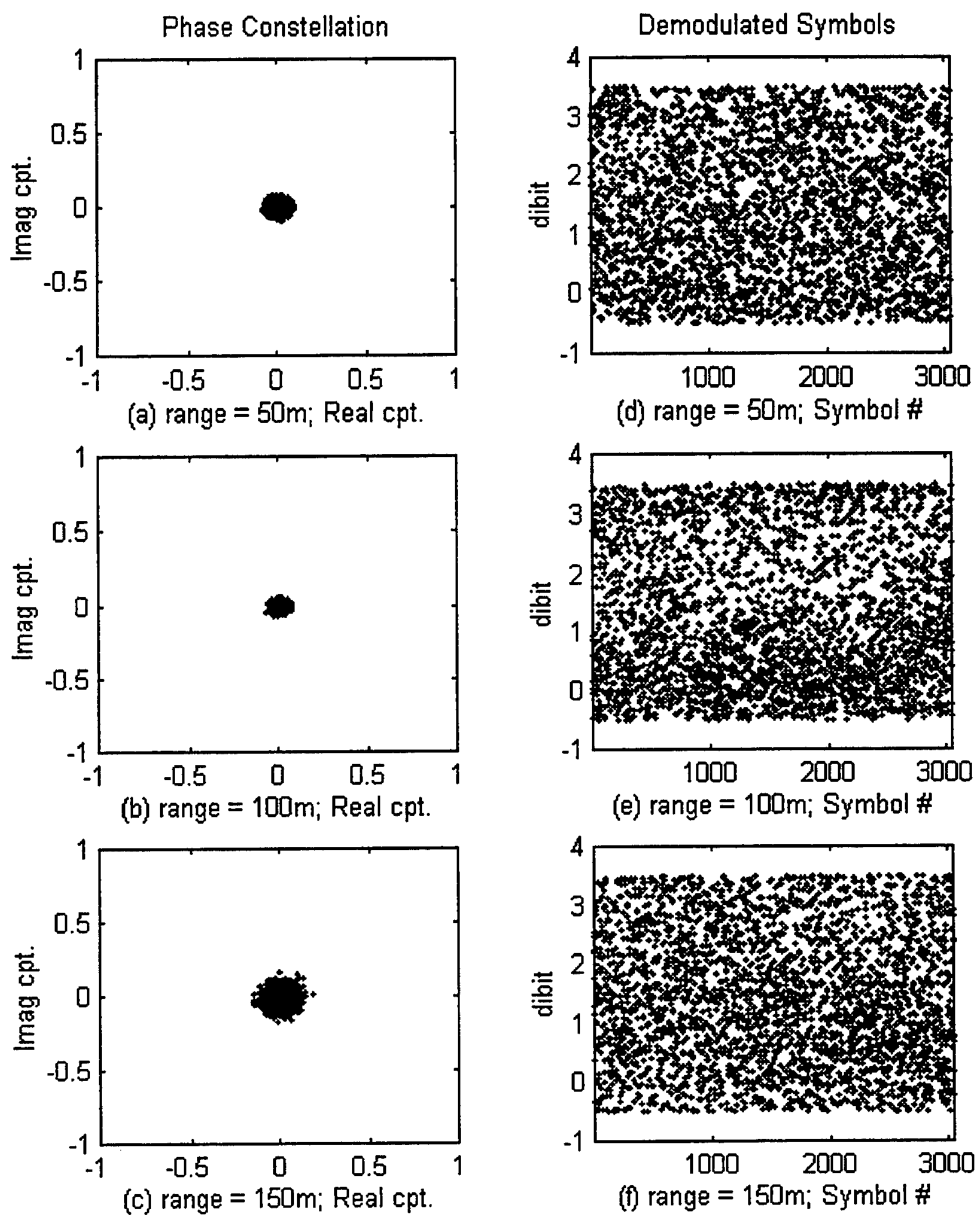


Figure 13 LC10 hydrophone, received signal constellations (rx-depth=5m, tx-depth=20m)

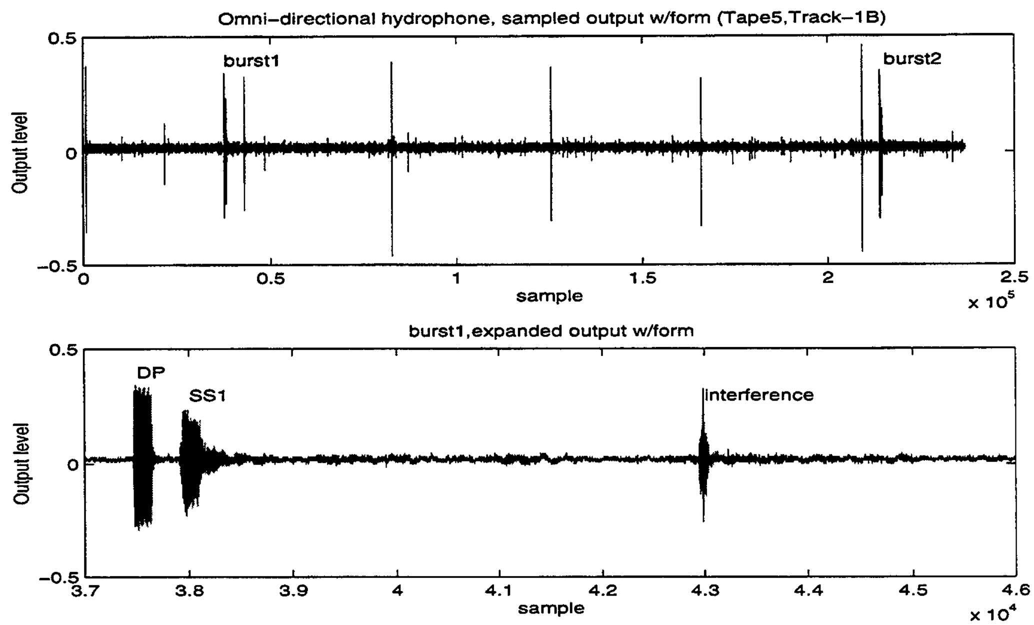


Figure 14 Burst transmission, LC10 hydrophone, range 50m (xscale: 1sec = 176,400 samples)

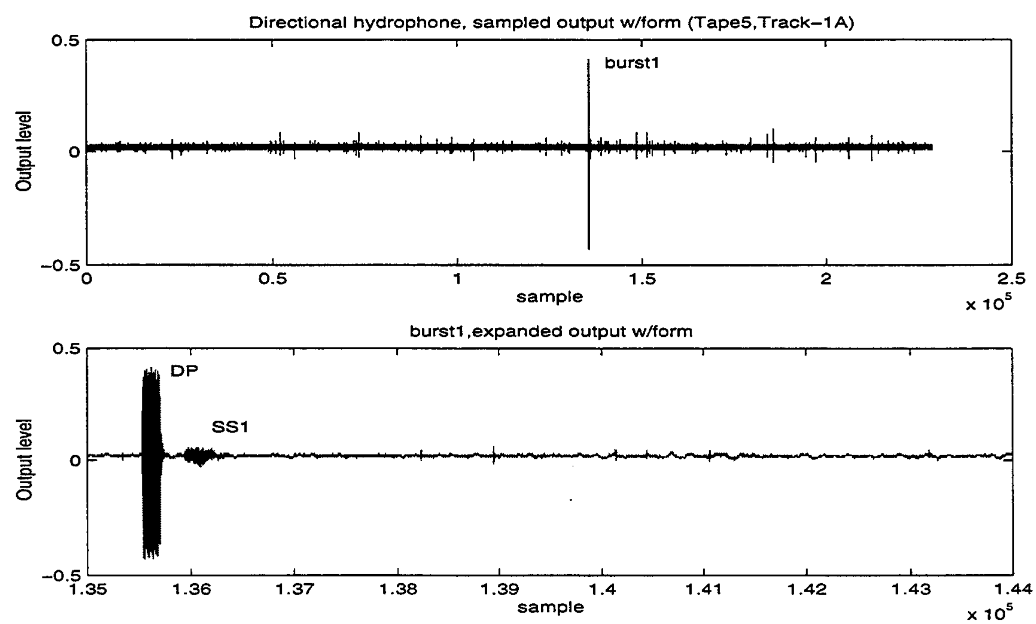


Figure 15 Burst transmission, ITC-3441 hydrophone, range 50m (xscale: 1sec = 176,400 samples)

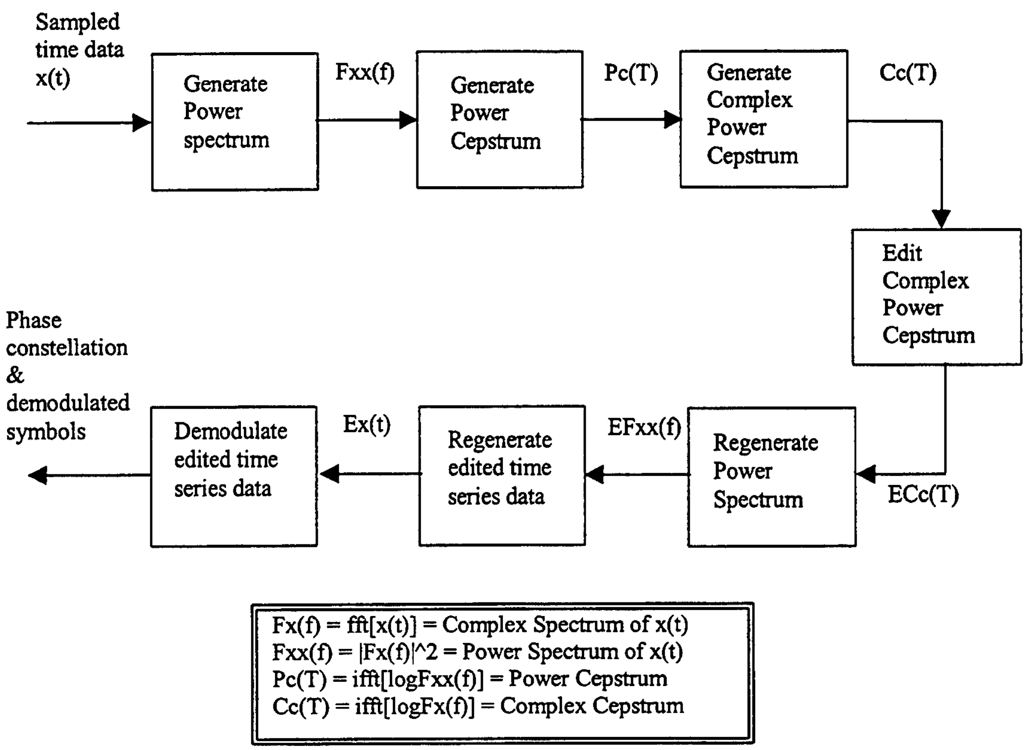


Figure 16 Cepstrum Analysis, sequence of operations

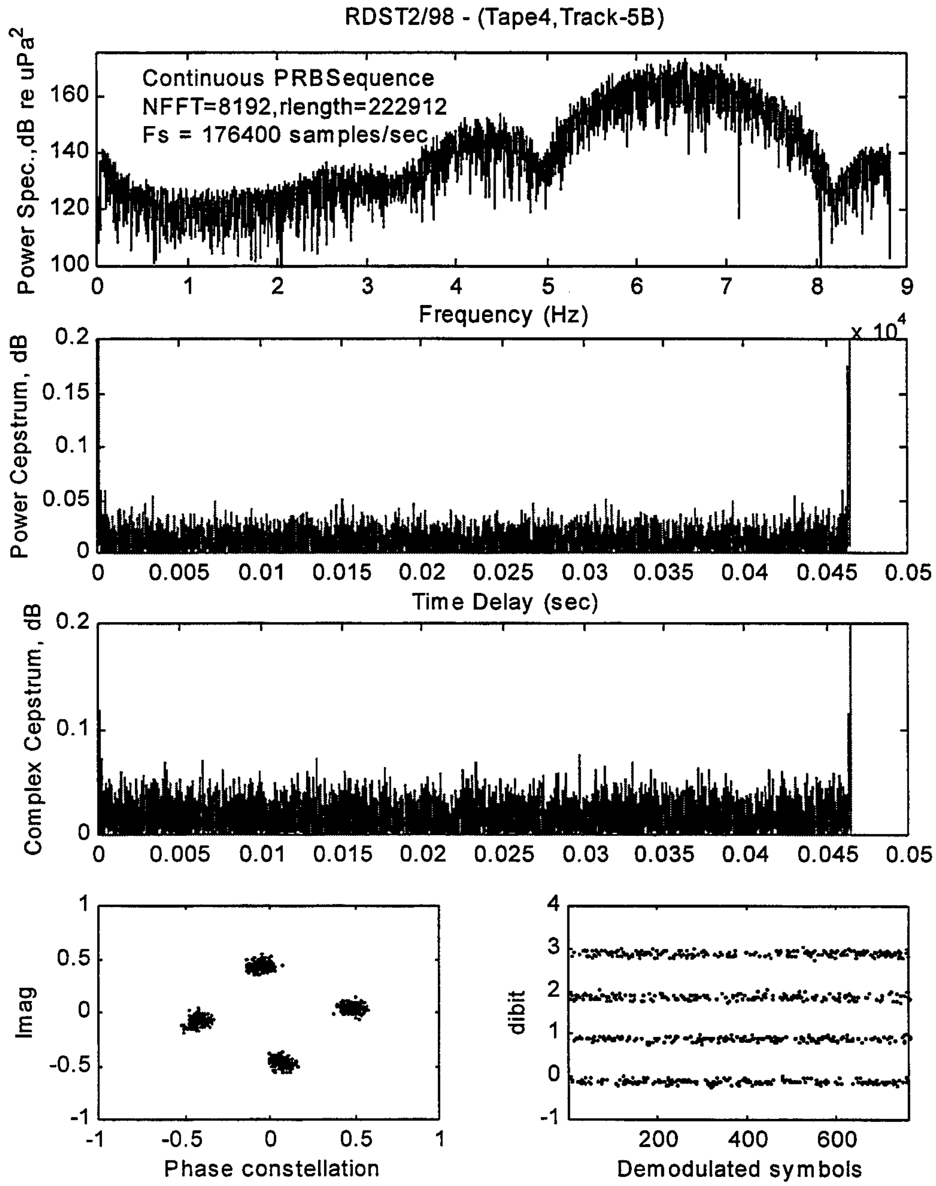


Figure 17 Cepstrum Analysis, ITC-3441 hydrophone (range=50m, rx-depth=5m, tx-depth=20m)

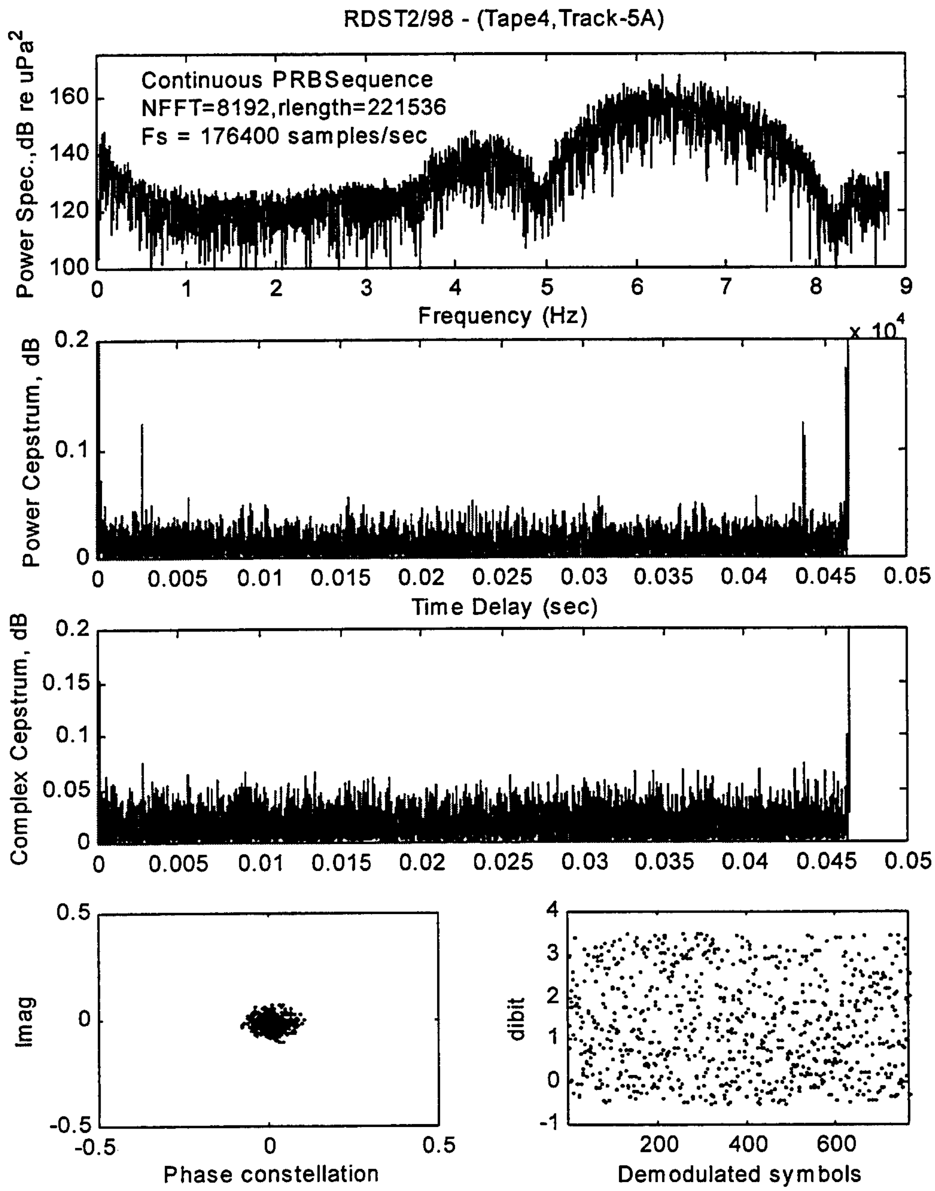


Figure 18 Cepstrum Analysis, LC10 hydrophone (range=50m, rx-depth=5m, tx-depth=20m)

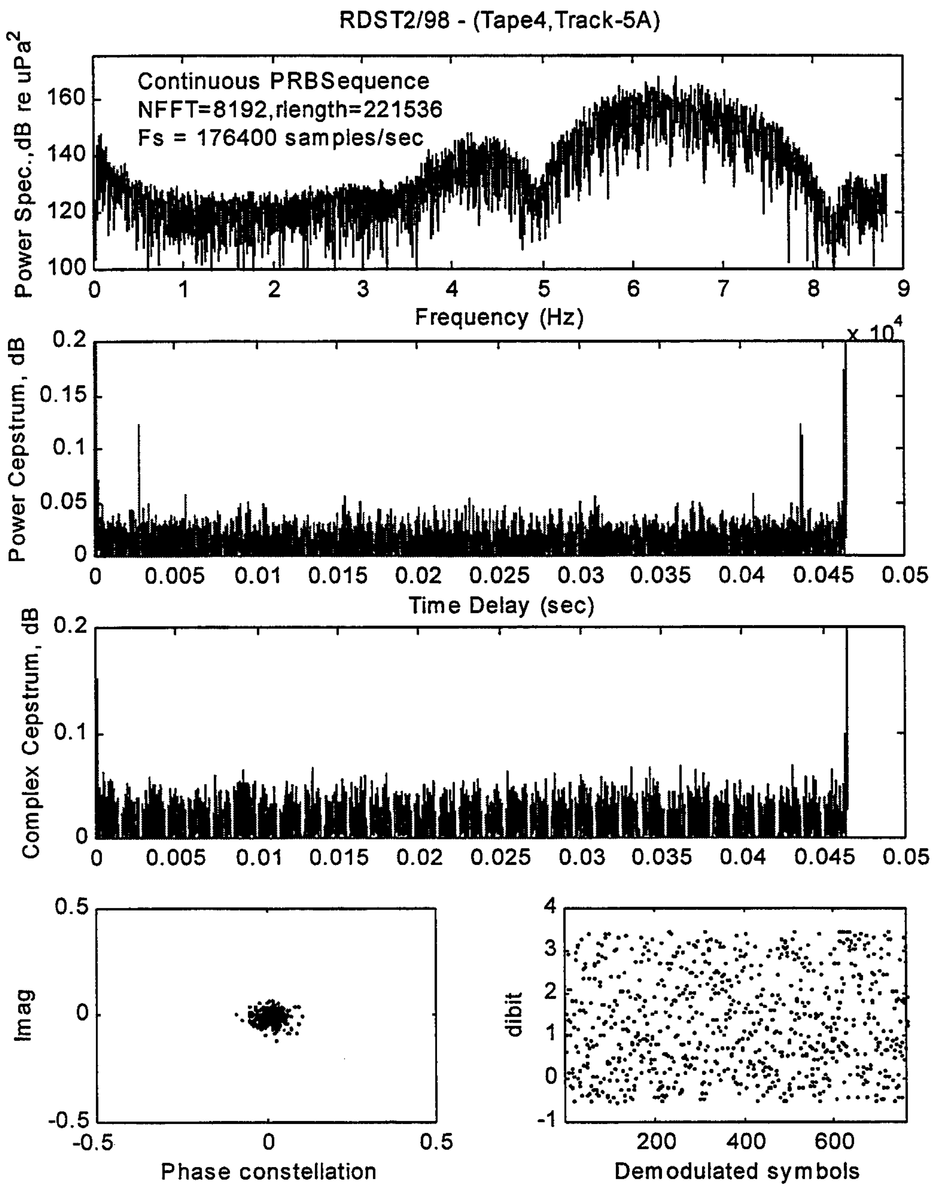


Figure 19 *Cepstrum Analysis, LC10 hydrophone, edited complex cepstrum (range=50m, rx-depth=5m, tx-depth=20m)*

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R. Alksne

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19. ABSTRACT

Maritime surveillance of Australia's littoral waters and approaches is important to the defence and well being of its resources. Rapidly Deployable Systems (RDS) that can be safely delivered and deployed, and then interrogated and controlled from near and/or far, may provide an important force multiplier for the ADF. However, the efficiency of these systems will, amongst other things, depend on the performance of the external data telemetry link. This is particularly true of an underwater acoustic communication or telemetry link that may be used by a patrol to interrogate and extract contact data from a surveillance barrier.

This paper describes work done by the Maritime Operations Division Salisbury, to design, develop, and trial a simple, low cost, high data rate underwater acoustic telemetry system in a shallow water littoral environment.